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INITIAL MIXING CHARACTERISTICS OF MUNICIPAL OCEAN DISCHARGES

VOLUME I - PROCEDURES AND APPLICATIONS

by

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FORWARD

A portion of this document is based on an earlier version by A.M. Teeter and D.J. Baumgartner (1979), which it supersedes. The technical reviews and resultant suggestions of A.R. Agg, W.A. Faisst, Irwin Haydock and P.J. Roberts resulted in many improvements and are gratefully acknowledged. We are also thankful to S.J. Wright, V.H. Chu, and other scientists who have indirectly contributed to the report in the form of fruitful dialogue during its development. Their continued inputs are encouraged, and will ensure timely publication of addenda and further improvements in future editions.

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Users of this document or the models described herein are encouraged to report any errors to enable appropriate corrections to be made. Direct all correspondence to D.J. Baumgartner, U.S. Environmental Protection Agency, Hatfield Marine Science Center, Newport, Oregon 93765. Holders of the document should notify the above to receive errata or future revisions to the document.

ABSTRACT

This report describes the behavior of plumes generated when wastewater is discharged at depth into waters of greater density. Volume I contains analytical solutions and descriptions of five mathematical models that provide the initial dilution and rise-height of the plume for a variety of discharge, diffuser, and receiving water characteristics. Initial dilution is defined as the flux-average dilution when the rising plume reaches an equilibrium level or encounters the surface. Guidance is provided for the range of values within which analytical solutions provide acceptable estimates. Use of the models is recommended for conditions outside these ranges and for detailed analysis. The format of model input data is the same for all five computer programs. As an option, the user may interact (via a terminal) with the models, changing one or more discharge parameters while holding the others constant and rerun the model without reentering existing ambient data. Any number of data sets may be stacked and all the programs have a subroutine (LIMITS) to check that certain input data are within prescribed limits. Example problem calculations are provided for each model. Complete program listings in FORTRAN IV-PLUS are provided in Volume II.

Volumes I and II are available in hardcopy from the National Technical Information Service (5285 Port Royal Road, Springfield, VA, 22161; 703-487-4650). Volume II is also available from NTIS on a 9-track tape or diskette (703-487-4763). The IBM-PC compatible diskette has programs slightly altered to compile using Microsoft FORTRAN (Version 3.1 or higher) or IBM Personal Computer Professional FORTRAN (8087 or 80287 chip required).

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model output descriptions)

y Horizontal distance 90° to x (see model output descriptions)

z Vertical distance upward from the discharge point or downward from the surface (see particular model output descriptions)

δ Characteristic radius or half-width of the plume = W/2

Δ Normalized density disparity $(\rho_\infty-\rho)/(\rho_0-\rho_d)$

Δ_0 Initial density disparity of the waste $=\rho_0-\rho_d$

ρ Average density of the plume, or UMERGE element average density

ρ_0 Ambient density at the level of the discharge, or at the UMERGE element boundary

ρ_d Density of the discharge

ρ_1 Centerline density at the end of the zone of flow establishment

ρ_∞ Ambient density at some level

ρ_s Ambient density at the surface

$d\rho/dz$ Ambient density gradient

SECTION 1

INTRODUCTION

Initial dilution is considered to be the rapid turbulent mixing which occurs between wastewater discharged at depth and the surrounding seawater resulting from the jet velocity at the point of release, driven by momentum and buoyancy in the plume relative to the ambient. The understanding of this mixing process can be used to predict the initial dilution attained under given conditions. Such predictions are used to design ocean outfalls, i.e., to select the number, spacing, size, and orientation of ports, and the depth of the discharge so that water quality criteria are met following initial dilution.

This report presents procedures for calculating the initial dilution and for describing the zone of initial dilution near a discharge site. Such calculations are required under U.S. Environmental Protection Agency regulations effective December 27, 1982 (U.S. EPA 1982), that implement Section 301(h) of the Clean Water Act (PL 97-117).

Two technical monographs provide detailed introductions to the general areas of marine outfalls and environmental hydrodynamics. The book of Grace (1978) discusses the characteristics of effluent wastewater; biological, chemical, and physical oceanographic factors which influence the engineering design of an outfall; and the construction and maintenance of an outfall. The general physics of mixing in rivers, reservoirs, estuaries, and coastal waters is explained in the work of Fischer et al. (1979). Useful discussions relevant to the papers described in the present report include theoretical and experimental bases of methods employed in determining the behavior of turbulent jets and plumes, and the (hydraulic) design of ocean outfalls.

MIXING ZONE CONCEPTS

When municipal wastewater is injected into the ocean, buoyancy and momentum combine to form a plume of increasing size as it rises toward the surface entraining seawater as a function of distance traveled. The entrainment process slows markedly when plumes reach a position of neutral buoyancy with respect to the ambient or when the plume surfaces. The dilution process subsequently becomes more dependent on ambient oceanic processes. Thus, the zone where <u>rapid</u> mixing takes place initially between the waste stream and the ambient can be physically distinguished from the zone where subsequent ambient conditions influence dilution. For purposes of regulating discharges under Section 301(h), this zone of rapid mixing is approximated by a defined "Zone of Initial Dilution". Water quality criteria should be met and water quality standards must be met outside this zone. Concentrations of those pollutants identified in the waste might then exceed water quality criteria within the initial dilution zone for a time which varies depending on the oceanographic and discharge factors influencing plume formation. This has been found to be on the order of several minutes for municipal discharges in the coastal waters of the United States. Marine organisms entrained in the plume, or passing through it, would thus be exposed to concentrations exceeding the level outside this zone for only a few minutes. Under these exposure conditions, the marine uses to be protected by water quality standards based on soluble concentrations are adequately addressed. Since some pollutants are not permanently dispersed by the initial dilution process, e.g. accumulation in surface films or sediments, and some adverse biological impacts may occur in spite of large initial dilution factors, e.g. bioaccumulation in organism tissues, biological and chemical tests of impacts within and beyond the zone of initial dilution are employed in the 301(h) process in addition to water quality criteria following initial dilution.

OCEAN DISCHARGES

Marine outfalls designed to discharge municipal wastes have a wide variety of physical characteristics which can affect initial dilution. Although single port outfalls are still used, many outfalls now have multiple ports to optimize the vertical rise and dilution attained. The size and number of ports, and their orientation, can significantly influence discharge patterns and achievable dilutions. The discharged material is relatively uniform, having physical characteristics similar to freshwater. The marine environment, however, varies greatly along the coastline and the physical conditions at the discharge site have a significant effect on initial dilution. The ambient receiving waters are of a higher density than the waste discharge and are frequently vertically stratified. Currents are usually present, and may have a tidal periodicity.

Discharges typically have fluxes of both momentum and buoyancy. The densimetric Froude number describes the ratio between the inertial and gravitational forces. The higher the initial Froude number, the more closely the resulting plume resembles a momentum jet. The smaller the number, the more the plume resembles a purely buoyant plume. While the differences influence the rate of dilution and the trajectory of the forced plume which is formed, there is not a great difference in the appearance of the plume. Because the density difference between the waste and the ambient varies only slightly and jet velocity is bounded by practical considerations, Froude numbers for municipal ocean discharges generally vary between 10 and about 30 (Grace, 1978). The ends of this range are characteristic of single-port and multi-port diffusers, respectively. In this range of Froude numbers, buoyancy is likely to dominate the initial mixing process, making volume rate of discharge, currents, ambient stratification, and possibly water depth, important. Especially in a current, buoyancy dominates since the plume's momentum becomes insignificant compared to the momentum entrained from the ambient.

Existing coastal discharge sites vary in depth up to about 75 m (246 ft). The water columns at these sites are typically stratified due to vertical variations in temperature and/or salinity. This leads to density stratification that varies widely in time and space. The proximity of large fresh water sources, surface heating, upwelling, and wind mixing all can influence density stratification. Also, salt wedges which typically occur near the mouths of estuaries having large freshwater flows cause large vertical and horizontal density gradients. Advection and nonlinear interactions between turbulent surface waters and deeper stratified waters also can produce pycnoclines or areas of pronounced density gradients. Winds of sufficient strength and duration can erode the density gradient by the turbulence they produce, leaving the ambient well mixed and allowing buoyant plumes to rise to the surface.

Currents are very complex in coastal areas where high energy is present from a number of processes. Nearshore currents at discharge sites may have tidal components which can be strong. Oceanic currents impinge on the coast and intensify on the western edges of the oceans (e.g., Florida Current). Local forces such as wind shear and waves also generate currents. Instantaneous current values (time scale of minutes), rather than long-term net currents (time scale of hours, days, etc.), are important in the initial dilution process.

BUOYANT PLUME MODELS

Ocean outfalls can be modeled by properly scaled hydraulic models, or by mathematical models. In some cases involving complex geometry or other conditions which cannot readily be incorporated into mathematical models, hydraulic modeling may be appropriate. Mathematical models have been used to study the characteristics and behavior of plumes and jets in both marine and freshwater settings, and in the atmosphere. Only mathematical models are considered in the remainder of this report.

Early work in this field was concerned with convection of purely buoyant plumes having no initial momentum. Rouse et al. (1952) studied the buoyant plume above a continuous heat source in an unstratified (uniform), stagnant environment. Equations of mass continuity, momentum, and energy were integrated by assuming Gaussian approximations for the lateral distributions of velocity and temperature across the plume and with experimentally determined spreading coefficients. The results were used to describe the distribution of velocity and temperature as functions of mass flow and height of rise. Priestly and Ball (1955) studied thermal plumes issuing into a stratified, as well as uniform, environment. They used essentially the same equations as Rouse et al. (1952) for mass, momentum, and energy, but their lateral Gaussian profiles of temperature and velocity assumed a lateral length scale.

Morton et al. (1956) also studied buoyant plume convection. They introduced an entrainment function based on local characteristic plume velocity and length scale to replace the spreading ratio. This approach has been adapted by many subsequent investigators (Baumgartner and Trent 1970). Later, Morton (1959) assumed other lateral profiles of velocity and temperature to account for the difference between eddy transport of heat and momentum. The value of this coefficient was estimated from experimental data.

Abraham (1963) investigated horizontally and vertically oriented jets discharging into stagnant homogeneous and stratified fluids. Equations of mass, momentum, and energy were integrated using lateral Gaussian profiles recognizing the difference in transfer rates between momentum and heat (or concentration). Entrainment was considered by integrating the continuity of mass equation with appropriate spreading coefficients. Abraham's results included analytical expressions for plume centerline velocity and concentration as a function of initial plume characteristics, height of rise, and entrainment coefficients for momentum and heat.

Fan (1967) reported on plumes issuing at arbitrary angles into a stagnant, stratified environment. Velocity and buoyancy profiles were similar to those used by Morton (1959) and included a lateral characteristic length. Solutions were found by simultaneously solving six equations (continuity of mass, vertical momentum, horizontal momentum, conservation of buoyancy, vertical geometry, and horizontal geometry).

Fan (1967) also investigated buoyant plumes in a flowing, uniform-density ambient. A theoretical solution was given as a function of plume drag forces and an entrainment function. The entrainment function was such that drag and entrainment coefficients varied with plume conditions, a disadvantage in applications beyond the range of experimental validation (Abraham 1971). Abraham introduced an entrainment function based on subdomains influenced by initial momentum and buoyancy. With entrainment coefficients defined for these two subdomains and a single coefficient describing the drag force, the theoretical solution was in good agreement with the experimental results of Fan. More recently, Chu (1979) and Wright (1984) have discussed buoyant plume dilutions and trajectories in cross flows in both uniform and stratified ambients.

Plumes from multi-port discharges have been studied less extensively. Pearson (1956) considered flow from a line diffuser in a stagnant medium in which merging of the individual jets had occurred. Liseth (1970, 1976) did experimental work on merging round buoyant jets from a row of ports in a line diffuser. Koh and Fan (1970) proposed a mathematical model of multi-port diffusers by interfacing single jet and slot jet solutions at a transition point. Cederwall (1971) studied the flow regimes of line sources for discharges in confined and unconfined environments. Sotil (1971) proposed a mathematical model for slot jets or continuous line sources in stagnant, stratified ambients. Kannberg and Davis (1976) examined the mixing characteristics of a multiport, submerged, thermal diffuser discharging into a uniform ambient as a function of port spacing, discharge Froude number, discharge angle and discharge-to-ambient velocity ratio. More recently, Roberts (1977; 1979a,b) examined line plumes discharging into steady currents. A number of excellent plume modeling reviews have been published (Briggs 1969; Baumgartner and Trent 1970; and more recently Davis and Shirazi 1978) and Roberts (1983, 1984, 1985) have summarized recent applicable modeling efforts.

Five computer models are described in this report. They include modified versions of PLUME, OUTPLM, and DKHPLM described in Teeter and Baumgartner (1979), and two additional models entitled UMERGE and ULINE. All of the models accept a variety of density gradients (i.e., zero, linear, or non-linear). The model PLUME by Baumgartner et al. (1971) simulates a solitary plume in a stagnant environment. OUTPLM by Winiarski and Frick (1976) also models a single plume, but in either a stagnant or uniformly flowing ambient. A revised version of DKHPLM by Davis (1975) describes single plumes which are allowed to merge with identical adjacent plumes in either stagnant of flowing environments with a variety of velocity profiles (i.e., zero, constant, or varying with depth). UMERGE, based on the work of Frick

(1981) also accounts for interference of adjacent plumes for a variety of current speeds. ULINE, based on Roberts (1977; 1979b) models a line source of finite length or closely spaced ports in a current flowing at an arbitrary direction and speed. Complete FORTRAN IV-PLUS program listings of each of the five models are available in Volume II of this report.

To simplify the use of these models, all have been tailored to read a single input file termed the Universal Data File. To indicate this modification, the names of the models have been preceded with the letter U. Hence the model designated in earlier work as PLUME is referred to in this report as UPLUME. In addition, DKHPLM has been changed to accept density and current profiles, and is renamed UDKHDEN.

Simplified analytical solutions are provided as they were in Teeter and Baumgartner (1979). However, they have been revised to reflect published experimental data. Dilution and trajectory equations are provided for single and merging forced plumes in both stagnant and flowing environments which have no density gradient or are linearly stratified. Approaches to solving equations for non-linear stratifications are cited. Example calculations are included for most conditions to assist the user in performing similar determinations. The analytical solutions are useful in situations where the models are not available, or where it is impractical to run a computer model.

REPORT ORGANIZATION

Section 2 presents general methods for determining plume initial dilutions, approaches to defining the critical minimum initial dilution and mixing zone concepts. Plume modeling parameters are presented in Section 3, followed by analytical solutions for selected discharges and receiving water conditions. Five numerical models are described in Section 4, and Section 5 is devoted to an explanation of the Universal Data File and numerical model execution. Required input data parameters are summarized along with tables of output parameters and a test run printout for each. The appendices contain a detailed description of the Universal Data File and the development of average dilution and height of rise relationships.

SECTION 2

INITIAL DILUTION

METHODS

The buoyant-plume phase of waste dispersion can be described by a variety of published methods. However, to evaluate the water quality impacts of municipal ocean discharges, the methods presented here are well suited and recommended for consistency. Some of these may be applicable to streams, rivers and lakes, although emphasis herein is on ocean discharges. Application of the models to these other environments may require additional caveats. For most cases, either analytical methods or computer models can be used. When there is uncertainty about the influence of simplifying assumptions, or when more detail is required, the computer models should be used. For unusual situations or conditions, other methods such as physical models should be considered. Although these models are felt to be reliable, they should be continually evaluated relative to theoretical developments and especially, quality field measurements.

APPROPRIATE CONDITIONS

Dilution is herein defined as the total volume of a sample divided by the volume of effluent contained in it. The dilution achieved during the initial mixing process is dependent on ambient and discharge conditions and is, therefore, highly variable. To prevent or minimize biological effects, occurrences of pollutant concentrations greater than limiting water quality criteria must be avoided. In evaluating a discharge's effect on water quality, therefore, the appropriate conditions to consider are those which result in the "lowest" dilution and those which occur at times when the environment is most sensitive. For example, minimum dilution can be predicted using a combination of maximum vertical density stratification, minimum initial density difference between the effluent and the ambient seawater, maximum waste flow rate, and minimum currents for a particular site. Other situations may be more critical depending on the ambient water quality, and applicable criteria.

Predicting dilution reliably depends on the availability of statistically valid data with which to estimate ambient conditions. The statistical uncertainty in estimates of absolute worst case conditions is generally great. Also there are inherent biases to some oceanographic measurements. For example, current measuring instruments have finite thresholds. It therefore becomes difficult to distinguish low values (which may be as high as 5.0 cm/sec) from zeroes in these data sets. In estimating environmental conditions, a more reliable estimation can be made at the lowest 10 percentile on a cumulative frequency distribution. Data on ambient density structure are not routinely collected. Consequently, there is not usually an existing data set for the site under consideration. To increase the reliability of "worst-case" estimates, data should be evaluated not only for the discharge site but for nearby coastal areas of similar environmental setting.

Defining "worst-case" conditions as a combination of those conditions affecting initial dilution, each taken at the worst 10 percentile on cumulative frequency distributions, is recommended (Tetra Tech 1982). This approach allows a reliable estimation of these conditions to be made and prevents the unlikely occurrence of more extreme conditions from biasing the predictions. The probability of these conditions occurring simultaneously is much less than 10 percent, ensuring that the predicted dilution will be exceeded most of the time. Application of multiple "worst case" factors (i.e. flows, stratification and currents) to determine a minimum dilution must be done carefully, however, and in recognition of the criteria for which compliance is being determined. For example, although application of an absolute "worst case" dilution may be appropriate for determining compliance with an acute toxicity limit, it is more appropriate to identify the lowest 6-month median dilution to determine compliance with a 6-month median receiving water limitation.

To determine initial dilutions it is necessary to know specific characteristics of the discharge, the outfall and the receiving waters. The discharge volumetric flow rate and density are required. Alternately the effluent temperature and salinity (major inorganic ions contributing to density) can be used to estimate a density based on known relationships for seawater (U.S. Navy Hydrographic Office 1952). Municipal effluent densities typically range from 0.9970 to 1.0003 g/cm^3, and salinities range to 5 ppt. The highest 2-3 hour flow rate during a period of concern should be used to calculate the minimum initial dilution for that period. Data from the last 2 years or longer should be used to ensure that the flows are representative. The flow from each port, which is not necessarily uniform, can be determined from an evaluation of manifold hydraulics. If the flow distribution among all ports is relatively uniform, the total outfall flow divided by the number of ports can be used as the representative per-port flow rate. Relevant diffuser characteristics include number of ports, size, spacing, angle of discharge, and depth.

In running the models, the port diameter specified should be the effective diameter, reflecting the effects of the orifice on the contraction of the jet. This effective diameter can be specified in terms of an appropriate discharge coefficient and true port diameter (Fischer et al. 1979).

The principal environmental quantities to consider in dilution prediction are the ambient density stratification and local currents. These parameters should be considered for periods of maximum wastewater flow, any other periods of maximum loadings (e.g. canning seasons), times of seasonal maximum and minimum stratification, low ambient water quality, low net circulation or flushing and exceptional biological activity. The quantities selected to represent these periods should reflect lowest 10 percentile conditions. Current speed data usually consist of discrete values and can be ranked into cumulative frequency distributions to select the 10 percentile design current.

The worst stratification is that which results in the lowest dilution if other conditions are constant. If the density gradients are uniform with depth they can be ranked numerically. If not, measured profiles can be input to the computer models and the results used to rank the profiles.

MIXING ZONE SPECIFICATION

After initial dilution, the concentrations of waste constituents (C_f) are a function of the average dilution achieved (S_a) and their concentrations in the ambient (C_a) and the effluent (C_e)

$$C_f = C_a + (C_e - C_a)/S_a \quad (1)$$

If the effluent has been adequately treated and disposed of in an environmentally appropriate area, the final concentrations of various constituents should comply with applicable quality criteria.

The zone surrounding the discharge site which geometrically bounds the critical initial dilutions is termed the zone of initial dilution (ZID) to distinguish it from other mixing zone definitions. It defines, theoretically, a concentration isopleth. Thus, there would be a discrete ZID for each density and current velocity profile at each site. In practice, the ZID defined for Clean Water Act Section 301(h) purposes is regularly shaped (e.g., circular, rectangular or "Y" shaped) to encompass the set of theoretically calculated dimensions. The ZID does not attempt to describe the area bounding the entire initial mixing process for all conditions (e.g. high currents and low stratification) or the area impacted by the sedimentation of particulate organic material.

Within the ZID, concentrations of pollutants in the water column may exceed water quality criteria. There will be times when dilution will be much higher than calculated for critical conditions, and consequently water quality may be met within the ZID. Beyond the ZID boundaries water quality standards are expected to be met essentially all the time. If biological impacts are detected beyond the ZID they would not be expected to have been due directly to water column concentrations. Since the models do not attempt to predict physical, chemical, and biological accumulation of constituents following initial dilution, other methods must be included in a complete evaluation of biological impact beyond the ZID boundary. These methods should account for seabed accumulation of particulates, surface film concentration, and bioconcentration in tissues of marine organisms. If potential problems are identified with these methods, additional initial dilution may be required although additional treatment or pre-treatment control may be much more effective.

The ZID dimensions and location are defined to establish a sampling perimeter at which adherence to water quality criteria is to be evaluated through monitoring. These dimensions can be specified by analyzing model results for a range of critical conditions. However, it can be simply approximated using the height of rise predicted for the critical conditions as a radial distance measured horizontally from the outfall diffuser or port. This distance will often equal the depth of water at the discharge site. During periods of higher currents, the plume will be carried further horizontally and initial dilutions will be higher than predicted for the critical current conditions. The dilution achieved over that portion of the trajectory within the ZID, however, will be approximately equal to the initial dilution predicted for the critical conditions. The U.S. EPA accepts ZID dimensions equal to the water depth from any point of the diffuser, provided these do not violate mixing zone restrictions in applicable water quality standards (Tetra Tech 1982).

SECTION 3

MODELING PROCEDURES

APPROACH

The plume attributes of primary interest are the average dilution, position, and dimensions at the equilibrium level or end of convective ascent through the water column, whichever occurs first. For evaluation purposes, it is important to identify the lowest flux-average dilution and trapping depth anticipated during critical periods, which in turn serve as input to analyses of immediate and farfield impacts on water quality and biota.

Behavior of buoyant plumes can be mathematically modeled by properly considering mass, momentum, energy, and a scalar variable (e.g., salt) (Hirst 1971a). A form of entrainment function must be assumed and fitted to experimental data. Other assumptions generally made are that flows are steady and incompressible, pressure is hydrostatic throughout, the plume is fully turbulent and axisymmetric, and turbulent diffusion dominates and is significant only in the radial direction. Distributions of velocity and concentration may also be assumed. Plume solutions can be obtained in various ways. Often, systems of differential equations are integrated across the plume to reduce the variables to a single independent one, namely arc length along the plume axis.

Mathematical models of jet discharge are systems with internal variables (mass, momentum, and energy), external variables (discharge characteristics, ambient vertical density, and currents), and boundary mechanisms (entrainment). Equations can be used to describe the resultant plume's behavior in terms of principal quantities. For stagnant conditions, the principal quantities are initial density difference between the waste and ambient (Δ_0), ambient density gradient ($d\rho/dz$), and flow rate per port (Q) or flow rate per unit length (q). Current speed (U), if considered, is also a principal quantity.

ANALYTICAL SOLUTIONS

The remainder of this chapter is devoted to presenting equations that can be used to approximate the plume average dilution and rise height, knowing selected characteristics of the discharged waste, the diffuser, and the receiving environment. Environmental conditions addressed include single and merging plumes, in stagnant and flowing environments which are linearly stratified or have no density gradient. Approximations for nonlinear stratifications are also discussed. The objective of this chapter is to provide practical equations for typical ranges of parameters of interest. Example calculations are included to assist the user in performing similar calculations.

The equations provide approximate solutions in lieu of running a model. However, for more exact solutions, use of one or more of the models described in Section 4 is encouraged. Use of the Universal Data File allows the running of several models for a particular input data set, or multiple runs with any one model to examine the effects of input parameter variation.

Dilution/Equilibrium Height Relationship

As developed in Appendix I, the following general relationships apply to cross-sectional average plume dilution (S_a) and the equilibrium height of rise (h) of a buoyant plume (i.e., negligible initial momentum) in receiving waters with a linear density gradient.

Given that

$$S_a = \beta z^n \tag{2}$$

then

$$h = \{[(n+1)/\beta][g_d'/G]\}^{1/(n+1)} \tag{3}$$

where

$$G = -(g/\rho_o)(d\rho/dz) \tag{4}$$

and

$$g_d' = g(\rho_o-\rho_d)/\rho_o \tag{5}$$

Although authors of reviewed works present dilution and equilibrium height equations in a variety of forms, the above forms are generally used throughout this section. Where another author's work is referenced, equations will have been transformed to these forms to enable comparison of equations for the various ambient conditions and port configurations considered.

As the density gradient decreases, so also does the parameter G, resulting in an increasing equilibrium height of rise, h. It is at this height that the average density of the plume is equal to the density of the surrounding water. The value of h calculated with equation (3) cannot exceed the water depth. For a surfacing plume, the average dilution can be estimated using Equation (2), with the water depth H reduced to account for the thickness of the waste field.

Single Plume, Stagnant Ambient

The plume average dilution as a function of elevation above the discharge point, z, for a single port discharging at an arbitrary angle into a quiescent unstratified environment can be calculated using the following (based on Brooks 1973)

$$S_a = 0.155\ g_d'^{1/3}Q^{-2/3}z^{5/3} \tag{6}$$

From this expression, β is 0.155 $g_d'^{1/3}Q^{-2/3}$ and n=5/3.

Substituting into Equation (3) results in

$$h = 2.91\ g_d'^{1/4} Q^{1/4} G^{-3/8} \tag{7}$$

In deriving equation (7), the entrainment given by equation (6) is assumed to apply to both unstratified and stratified environments.

For unstratified conditions, the rising plume is deflected horizontally upon nearing the ocean surface. Compensation for this effect should be taken into account. Because the extent of any further dilution within the trapped wastefield is not well documented, dilution can be estimated by using an effective distance over which dilution is occurring equal to the full water depth minus the vertical thickness of the surface waste field.

Brooks (1973) suggests a correction in H of approximately one quarter the plume diameter, or 0.07z. Lee and Jirka (1981) indicate that, for large values of the water depth to port diameter ratio (i.e., >10), the waste field thickness is approximately 0.08 times the water depth for a vertical round buoyant jet. Frankel and Cumming (1965) reported a surface field thickness of 0.25 times the water depth for a horizontal round buoyant jet near the bottom. Fan and Brooks (1966) report that, in most cases, the surface waste field thickness is considerably less than one-fourth the water depth. They also report that the surface transition zone dimension is not a simple proportion of the water depth, but also of rising plume parameters (e.g. z/D, F), the discharge angle, and the character of the horizontal surface flow layer. An important parameter that may be dominant, but has not been mentioned in the papers reviewed, is the magnitude of the residual buoyancy possessed by a plume as the surface is reached. A large difference in buoyancy between the plume and the receiving water will force formation of a thinner layer than would a small difference.

In the absence of a clearly definitive value for the surfaced waste field thickness, a nominal value of one-tenth the water depth is used herein. Therefore equation (6) becomes

$$S_a = 0.155\ g_d'^{1/3} Q^{-2/3} (H-0.10H)^{5/3} \tag{8}$$

or

$$S_a = 0.130\ g_d'^{1/3} Q^{-2/3} H^{5/3} \tag{9}$$

When the height of rise computed using equation (7) reaches or exceeds 0.9H, then equation (9) should be used.

It should be noted that the equilibrium height of rise in UPLUME is the same as h in equation (3), namely the height in the water column where the average plume density equals the density of the surrounding ambient. UPLUME does, however, contain an algorithm to correct for a finite plume thickness of 0.1H at the surface. The earlier version of the model, PLUME, did not contain this correction.

Additional references for single buoyant jets in quiescent stratified environments include List (1982), Hofer and Hutter (1981), Henderson-Sellers (1978), Baines (1977), Cederwall (1975, 1968), Koh and Brooks (1975), Fox (1970), Abraham and Eysink (1969), Fan (1967), Abraham (1963), Hart (1961), Morton (1959), and Morton et al. (1956). References for single buoyant jets discharging into quiescent unstratified environments include Lee and Jirka (1981), Chen and Nikitopoulos (1979), Kotsovinos (1978), Schau (1978), Abraham (1978, 1963, 1960), Baines (1977), Cederwall (1975, 1968), Morton (1959), Morton et al. (1956), and Rouse et al. (1952).

In the following calculations, port spacing is assumed to be sufficiently large to preclude merging of adjacent plumes. Verification of noninterference can be made by estimating the plume half-widths at the equilibrium point or at the surface as appropriate, using the methods described in Fan and Brooks (1969), or in Brooks (1973).

Example--

A 50-port diffuser has a total flow rate of 2.19 m^3/sec (50 MGD) and a density of 0.9995 g/cm^3. The ambient at the discharge site has a surface density of 1.0246 g/cm^3 and, at a depth of 30.5 m (100 ft), a density of 1.0258 g/cm^3. Determine the maximum height of rise and average initial dilution.

$$g_d' = (9.81)[(1.0258-0.9995)/1.0258] = 0.2515 \text{ m/sec}^2$$

$$Q = 2.19/50 = 0.0438 \text{ m}^3\text{/sec}$$

$$G = -(9.81/1.0258)[(1.0246-1.0258)/30.5)] = 3.763\ (10^{-4})\ \text{sec}^{-2}$$

According to equations (6) and (7),

$$h = 2.91(0.2515)^{1/4}(0.0438)^{1/4}[(3.763)(10^{-4})]^{-3/8} = 18.1 \text{ m}$$

$$S_a = 0.155\ (0.2515)^{1/3}\ (0.0438)^{-2/3}(18.1)^{5/3} = 98$$

For this example, assume that the ambient density gradient is zero. The surfacing plume average dilution according to Equation (9) is

$$S_a = 0.130(0.2515)^{1/3}(0.0438)^{-2/3}(30.5)^{5/3} = 197$$

Single Plume, Flowing Ambient

The appropriate form of plume initial dilution and trajectory equations when a crossflow is present depends on whether the plume is momentum- or buoyancy-dominated at the point of consideration, and whether it is in the nearfield or farfield region. Wright (1984) provides minimum dilution and trajectory equations for each of the four possible combinations of conditions. The subsequent discussion is limited to the buoyancy-dominated farfield condition most likely to apply to plumes at the point of equilibrium in a flowing environment.

The average dilution S_a can be computed with

$$S_a = C(U/Q)z^2 \tag{10}$$

where $\beta = C(U/Q)$ and $n=2$, which is analogous to equation (2).

Using the method of Chu (1979, 1985), the average dilution of a plume in a crossflow, in the buoyancy dominated farfield can be expressed as:

$$S_a = 0.49(U/Q)z^2 \tag{11}$$

Substituting $\beta = 0.49(U/Q)$ and $n=2$ into equation (3) gives

$$h = 1.83[(Q)(\rho_o - \rho d)/(U\ d\rho/dz)]^{1/3} \tag{12}$$

For a stratified flowing ambient, Wright (1984) provides the following relationship for the equilibrium height of rise

$$h = 1.85\ (U/\varepsilon^{1/2})^{2/3}\ (B/U^3)^{1/3} \tag{13}$$

where

$$\varepsilon = -(g/\rho_o)d\rho/dz$$
$$B = g_d'Q = [g(\rho_o - \rho_d)/\rho_o]\ Q$$

Substituting these identities, Equation (13) can also be written as

$$h = 1.85\ [(Q)(\rho_o - \rho_d)/(U\ d\rho/dz)]^{1/3} \tag{14}$$

which is in close agreement with Equation (12).

In a crossflow, a blocking correction for a surfacing plume may be appropriate (Roberts, P.J.W., 9 October 1984, personal communication). In the absence of experimental data, it is assumed that the proper elevation at which dilution should be determined is the plume centerline as the plume touches the surface. As shown in Figure 1, the plume centerline lies an

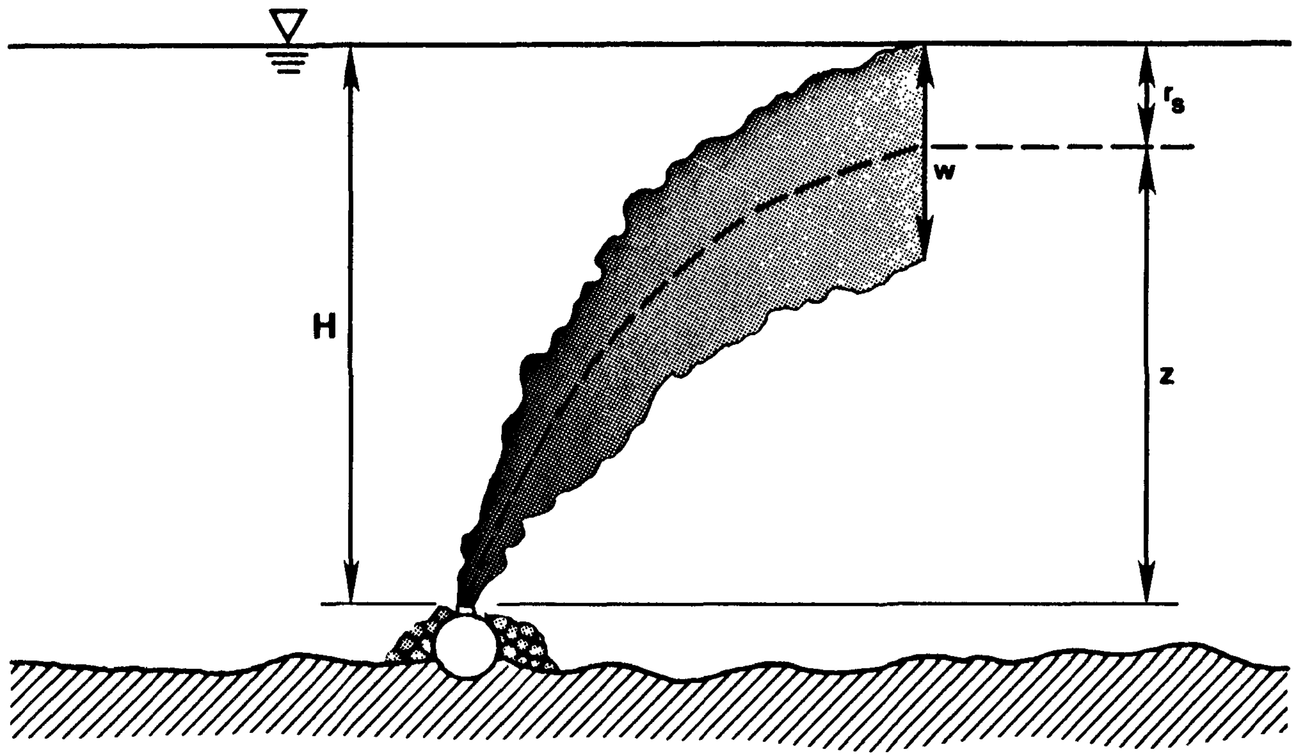


Figure 1. Buoyant plume trajectory in an unstratified crossflow.

amount r_s below the water's surface. Chu (1979) gives a linear relationship between plume width and height z above the discharge point (based on observed plume dye boundaries), when the exit-to-crossflow velocity ratio exceeds four

$$W = 0.68z \tag{15}$$

or

$$r_s = W/2 = 0.34z \tag{16}$$

Therefore

$$z = H - r_s = H - 0.34z$$

or

$$z = H/1.34 = 0.746H \tag{17}$$

Substituting this value of z into Equation (11) gives

$$S_a = 0.27\ (U/Q)H^2 \tag{18}$$

Wright (8 April 1985, personal communication) suggests that blocking effects are much smaller than previously reported. Taking this into account (i.e., let z=H), using his 0.4 coefficient for axis-of-symmetry dilution, and an averaging factor of 0.72 results in

$$S_a = (0.4)(0.72)(U/Q)z^2 = 0.29\ (U/Q)H^2 \tag{19}$$

which is within 10 percent of Equation (18).

Single buoyant jets discharging into a flowing, linearly stratified ambient are discussed by Manins (1979), Schatzmann (1978), Henderson-Sellers (1978), Luti and Brzustowski (1977), Hayashi (1972), and Hirst (1971b). Additional references for single buoyant jets discharging into an unstratified environment with a significant current include Crabb et al. (1981), Hwang and Pletcher (1978), Schatzman (1978), Abraham (1978), Abdelwahed and Chu (1978), Krausche et al. (1978), Baines (1977), Jiji and Hoch (1977), Wright (1977), Chien and Schetz (1975), Chu and Goldberg (1974), Hayashi (1972), Hoult et al. (1969), and Fan (1967).

Example--

A 0.5 m^3/sec (11.4 MGD) municipal effluent is discharged from a single port in 50 m (164 ft) of ocean water. The discharge density is 1.000 g/cm^3, and ambient density varies linearly from 1.0260 g/cm^3 at the discharge depth to 1.0240 g/cm^3 at the surface. Ambient current speed is 15 cm/sec (0.49 ft/sec). Determine the plume equilibrium height of rise, and the average dilution.

Calculate

$$d\rho/dz = -(1.0240-1.0260)/50 = 4x10^{-5} \text{ g/cm}^3\text{/m}$$

Equations (11) and (12) give

$$h = 1.83[(0.5)(0.026)/(0.15)(4x10^{-5})]^{1/3} = 23.7 \text{ m}$$

$$S_a = 0.49 \ (0.15/0.5)(23.7)^2 = 83$$

If the receiving water was unstratified (i.e., $d\rho/dz=0$), the corresponding average dilution upon surfacing would be according to Equation (18)

$$S_a = (0.27)(0.15/0.5)(50)^2 = 203$$

Merging Plumes, Stagnant Environment

At a given height, z, above a diffuser which has ports spaced at an interval, l, little merging occurs provided the ratio of z/l<5. As z/l increases beyond five, there is a significant decrease in the dilution rate due to merging of adjacent plumes, and a 2-dimensional plume condition is approached. There are two approaches to expressing the results for an unstratified environment. One explicitly considers the effects of blocking, whereas the other includes blocking implicitly. If blocking is ignored, then for an unstratified ambient, the average initial dilution can be expressed as

$$S_a = 0.54 \ (g'/q^2)^{1/3} \ H \tag{20}$$

(Brooks 1973; Fischer et al., 1979). However, the average initial dilution observed at the edge of the zone of initial dilution includes blocking, which can be taken into consideration by assuming that the waste field has a finite thickness and that dilution ceases at its lower boundary.

Koh (1983) suggests that blocking is significant and reports that the thickness for laboratory multi-port diffusers varies from less than 30 to about 40 percent of the water depth, as reported by Liseth (1970), Buhler (1974), Liu (1976), Koh (1976), and Roberts (1977). Roberts measured minimum near-surface dilutions whose magnitudes correspond to those calculated using Equation (20) at a height of 0.7 times the water depth, with the coefficient decreased by a factor of 1.41 (to 0.38). This suggests that dilution ceases in the upper 30 percent of the water column. In contrast, Wright (1985) cites evidence that blocking is minimal, and suggests that until a more complete analysis is developed, the buoyant jet formula should be applied all the way to the surface in an unstratified environment, and to the maximum height of rise in a stratified environment.

Pending resolution of this issue and in the interests of determining compliance with water quality criteria, the dilutions calculated herein are conservatively determined at the lower boundary of the waste field in an unstratified environment, and at the equilibrium height in a stratified environment. Therefore, a correction to equation (20) can be made as follows

$$S_a = 0.54 \ (g'/q^2)^{1/3} \ (H-0.3H)$$

or

$$S_a = 0.38\ (g'/q^2)^{1/3}\ H \tag{21}$$

The second approach, which implicitly includes the effects of blocking (Roberts, P.J.W., 25 July 1985, personal communication), employs the experimental results of Roberts (1977). The average initial dilution achieved by a line source in a slowly moving unstratified ambient flow is expressed as

$$S_a = 0.38\ (g'/q^2)^{1/3}\ z \tag{22}$$

provided the ratio of ambient current velocity cubed to buoyancy flux per unit length is sufficiently low, that is

$$F = U^3/g'q \leq 0.1 \tag{23}$$

The constant in Equation (22) includes a factor of 1.41 to convert the measured minimum near-surface dilution to an average dilution for a line source (Fischer et al. 1979).

The entrainment parameter β based on Equation (22) is assumed to be valid for stratified conditions. The equations for equilibrium height and dilution for these conditions can be deduced from the form of Equation (22). Since β is $0.38(g'/q^2)^{1/3}$ and n=1, substitution into Equation (3) gives

$$h = 2.29\ (g'q)^{1/3}/G^{1/2} \tag{24}$$

Using this equilibrium height in the average dilution Equation (22) gives

$$S_a = 0.87\ (g')^{2/3}/(q^{1/3}G^{1/2}) \tag{25}$$

Further references on 2-dimensional slot jets discharging into a quiescent unstratified ambient include Fischer et al. (1979), Kotsovinos (1978), Liseth (1976, 1970), Cederwall (1975, 1971), Abraham (1963), and Rouse et al. (1952). Authors treating 2-dimensional buoyant jets in a quiescent stratified environment include Wright (1982), Sorrell and Smith (1981), Chen et al. (1980), Wright and Wallace (1979), Fischer et al. (1979), Cederwall (1975), Liseth (1970), and Abraham (1963).

Example--

Estimate the average initial dilution for an outfall whose volumetric flow rate is 4.38 m^3/sec (100 MGD). The water depth is 30.5 m (100 ft), port spacing is 1.5 m (5 ft), and the diffuser is 1,000 m (3,280 ft) long. Surface and bottom ambient densities are 1.0240 and 1.0258 g/cm^3, respectively. Effluent density is 1.0000 g/cm^3. Ambient current is constant with depth at 4 cm/sec (0.13 ft/sec).

To determine the applicability of Equation (25), calculate $z/l=30.48/1.5=20>>5$, suggesting merging. Also, $F=U^3/g'q$ is 0.06. Therefore, the equilibrium height and associated dilution can be calculated as follows

$$G = -(9.81/1.0258)[(1.0240-1.0258)/30.5] = 5.64\times10^{-4}\ \text{sec}^{-2}$$

Equations (24) and (25) give

$$h = 2.29[(0.253)(0.00438)]^{1/3}/(5.64\times10^{-4})^{1/2} = 10.0\ \text{m}$$

$$S_a = 0.87(0.253)^{2/3}/[(0.00438)^{1/3}\ (5.64\times10^{-4})^{1/2}] = 90$$

In the case of an unstratified environment, the near surface dilution using Equation (21) is

$$S_a = (0.38)(0.253)^{1/3}(0.00438)^{-2/3}(30.5) = 274$$

<u>Merging Plumes, Flowing Environment</u>

Roberts (1977) provides graphical solutions for vertical slot jets oriented at angles of 0^o, 45^o, and 90^o to the ambient current flow, for values of $F=U^3/b$ up to 100. For increasing values of F above 0.1, the effect of current angle becomes significant. For ambient flow perpendicular to the slot jet (θ=90°) and $0.2<F<100$, the initial dilution was found to be

$$S_a = 0.82(U/q)z \qquad (26)$$

Included in the factor 0.82 is a 1.41 multiplier to convert measured minimum near-surface dilution to an average dilution.

For the reduced dilutions found when the current flow is other than normal to a slot jet, the reader is referred to Figure 2. For $F=U^3/b=100$, and ambient flow parallel to the axis of the slot, measured dilutions were about 2.5 times greater than with no ambient current, compared to 10 times greater for the perpendicular flow condition.

For a linearly stratified environment with a relatively strong current (i.e., $F=U^3/b\geq 0.1$), which is perpendicular to a vertically oriented diffuser with merging plumes, the average initial dilution and height of rise can be expressed as follows. Since β is 0.82 U/q and n=1, the rise height, in the form of Equation (3) is

$$h = 1.56[(g'q)/(UG)]^{1/2} \qquad (27)$$

Substituting this value of h into Equation (26) gives

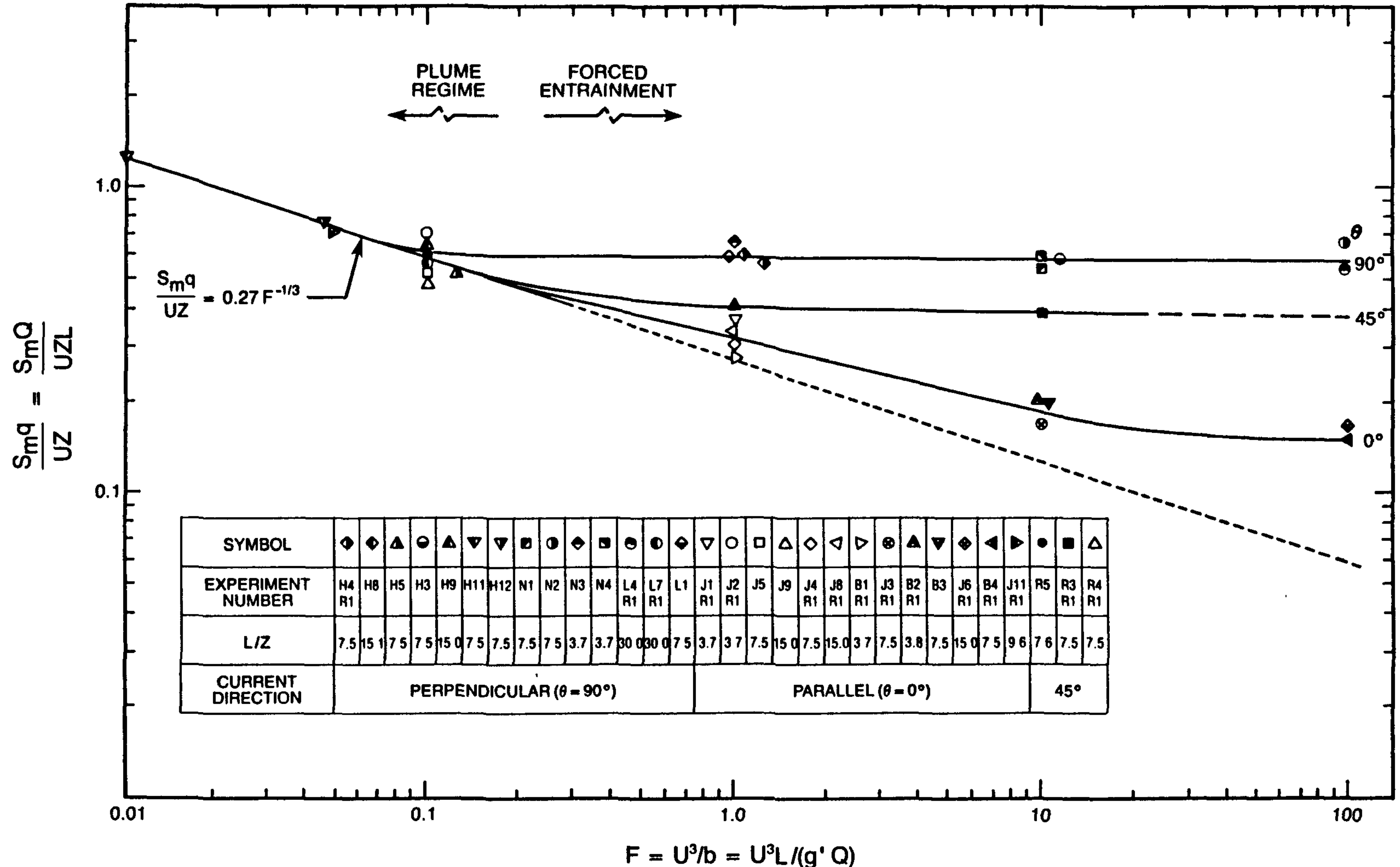
$$S_a = 1.28\ [(g'U)/(qG)]^{1/2} \qquad (28)$$

Example--

Determine the near-surface initial dilution for the same outfall and ambient characteristics given in the previous example, for an ambient current of 15 cm/sec (0.49 ft/sec).

The merging condition still applies since z/l is 20. To determine whether $F>0.1$ calculate

$$U^3 = (0.15)^3 = 0.0034\ m^3/sec^3$$



REFERENCE: Roberts 1977

Figure 2. Experimental measurements of minimum surface dilution for a finite line source of bouyancy flux in a current.

$$g' = (9.81)(1.0258-1.0000)/(1.0000) = 0.253 \text{ m/sec}^2$$

$$q = 4.38/1000 = 0.00438 \text{ m}^3\text{/sec/m}$$

$$F = 0.0034/(0.253 \times 0.00438) = 3.1$$

For stratified conditions, the equilibrium height and associated average dilution can be calculated using Equations (27) and (28) as follows

$$h = 1.56[(0.253)(0.00438)/(0.15)(5.64 \times 10^{-4})]^{1/2} = 5.6 \text{ m}$$

$$S_a = 1.28[(0.253)(0.15)/(0.00438)(5.64 \times 10^{-4})]^{1/2} = 159$$

Applying Equation (26) for an unstratified condition gives

$$S_a = (0.82)(0.15/0.00438)(30.5) = 857$$

APPROXIMATIONS FOR NONLINEAR STRATIFICATIONS

Brooks (1970, 1973) and Roberts (1979b) discuss general approaches to solving buoyant jet problems, i.e., direct computer solutions by models such as those presented herein, or by linear approximation of the measured density profiles. For most problems an approximate solution is obtainable by assuming an equivalent uniform density gradient over that portion of the water column over which the plume rises. The reader may consult Brooks (1973) for a graphical method of determining h, which can then be used to determine the initial dilution by previously presented methods.

OTHER DIFFUSER CONFIGURATIONS

Staged diffusers with ports oriented in the general direction of the pipe axis have been constructed. Authors who have addressed the dynamics of discharges from such diffusers include Adams and Trowbridge (1979), Trowbridge (1979), Chu (1977), Brocard (1977), and Almquist and Stozenbach (1976). Adams (1982, 1972), has examined the flow produced by unidirectional diffusers in both parallel and perpendicular ambient currents, comparing measured and predicted dilutions. Another form of diffuser currently receiving more consideration is the multiport riser. Isaacson et al. (1983, 1979, 1978a,b) examined the nearfield plume dilutions from an ocean outfall diffuser consisting of evenly spaced risers with clusters of two to eight ports. For additional information on jets and plumes from risers or other diffuser configurations, refer to the annual mixing and transport literature review in each June issue of the Water Pollution Control Federation Journal.

SECTION 4

NUMERICAL MODEL DESCRIPTIONS

INTRODUCTION

The theoretical developments of five numerical models are described in this section. UPLUME and UOUTPLM are essentially the same numerical models contained in Teeter and Baumgartner (1979). The model UMERGE is a generalization of OUTPLM to take into account the effects of plume merging. UDKHDEN is an improved version of DKHPLM described originally in 1979 (Teeter and Baumgartner), and ULINE is a generalization of the analytical formulas of Roberts (1977; 1979b). UPLUME and UOUTPLM accept multiple port data but do not consider the effects of merging. UOUTPLM accepts ambient current constant with depth in a direction perpendicular to the diffuser axis. The models UMERGE, UDKHDEN, and ULINE consider multiport diffusers in a stagnant or flowing environment in which the effects of merging are considered and the current speed, if present, is allowed to vary with depth. ULINE is the most simple while UDKHDEN is the most complex. A brief summary of the model characteristics is given in Table 1. The vertical extent of the ambient is considered infinite in the theoretical development of all the models e.g., there are no built-in plume-surface interactions, and flow is assumed to be fully turbulent. All models provide average dilutions, and UPLUME can optionally provide centerline dilution.

UPLUME

Theoretical Development

The computer model PLUME (Baumgartner and Trent 1970; Baumgartner et al., 1971) considers a buoyant plume issuing at an arbitrary angle into a stagnant, stratified environment. Two zones of plume behavior are con-

TABLE 1 . SUMMARY OF NUMERICAL MODEL CHARACTERISTICS

Parameter	UPLUME	UOUTPLM	UMERGE	UDKHDEN[a]	ULINE
Port[b]	single	single	multiple	multiple	slot/closely spaced
Discharge angle[c]	-5° to 90°	-5° to 90°	-5° to 90°	-5° to 130°	assumes 90°
Density profile	arbitrary	arbitrary	arbitrary	arbitrary	arbitrary
Current speed	no	constant with depth	arbitrary	arbitrary	arbitrary
Current angle relative to the diffuser[d]	n/a	assumes 90°	assumes 90°	45°-135°	0°-180°

[a] For a single port discharge the current angle may be in the range of 0° to 180°. For an angle greater than 90° the program converts it to the supplementary angle. (Note: 0° and 180° give the same results).

[b] All the models except ULINE reduce the data to a single port discharge. UPLUME and UOUTPLM detect merging of adjacent plumes and alert the user, but do not account for this in the remainder of the calculations whereas UMERGE and UDKHDEN do. ULINE converts the data to a slot discharge.

[c] The discharge angle limits are those allowed by the subroutines LIMITS in each of the programs. They are not necessarily the theoretical limits associated with these models. Caution should be exercised when using the models for angles beyond these limits.

[d] 90° is perpendicular to the diffuser. At a discharge angle of 0° (horizontal) and a current angle of 90°, the discharge and the current are parallel and in the same direction.

sidered. The region required to develop fully established profiles is the zone of flow establishment. Beyond this zone, similarity profiles are assumed for velocity and concentration. This allows the equations for mass continuity, momentum, and density disparity to be integrated across the plume reducing them to one independent variable, the arc length along the axis of the plume.

Zone of Flow Establishment--

The length of the flow establishment zone, s_e, has been found to depend on the initial Froude number, F (Abraham 1963). As initial Froude numbers approach infinity, s_e=5.6 port diameters. At low Froude numbers, this distance is shorter. The inclination of the plume's axis, θ_e, at s_e is a function of s_e, F, and the initial discharge angle. The centerline velocity at s_e depends on the Froude number and, for low Froude numbers, may be greater than the initial velocity due to the influence of buoyancy (Abraham 1963).

Zone of Established Flow--

The following assumptions are made

- Flow is steady and incompressible
- Turbulent diffusion is significant only in the radial direction
- Pressure is hydrostatic throughout
- Plume flow is axisymmetric
- Velocity and concentration distributions are Gaussian across the plume, so that

$$V/V_m = \exp\left[-k\ (r/s)^2\right] \tag{29}$$

$$\Delta/\Delta_m = C/C_m = \exp\left[-ku(r/s)^2\right] \tag{30}$$

where V and C are the velocity and concentration respectively, at some radial distance, r. The subscript m refers to the centerline. The distance along the plume's trajectory is s; k and u are empirical coefficients (Abraham 1963).

The governing equations are

Conservation of mass,

$$d/ds \int_0^\infty Vrdr = -r_b u_b \tag{31}$$

Conservation of vertical momentum,

$$d/ds \int_0^\infty V^2 rdr = \sin\theta \int_0^\infty [(\rho_\infty - \rho_d)/\rho_d]\ grdr \tag{32}$$

Conservation of density disparity,

$$d/ds \int_0^\infty V\Delta rdr = \int_0^\infty [Vr/(\rho_o - \rho_d)]\ (d\rho_\infty/ds)dr \tag{33}$$

Conservation of pollutants,

$$d/ds \int_0^\infty VCrdr = 0 \tag{34}$$

Substitution of equations (29) and (30) into these four equations, simplifying, and reducing to nondimensional form, these equations become

Momentum,

$$d/ds\ (V_m^3\ s^3/k^{3/2}) = [3g\Delta_m V_m\ s^3\ \sin\theta(\rho_o - \rho_d)]/(\rho_d u k^{3/2}) \tag{35}$$

Density disparity,

$$d/ds\ [(\Delta_m\ V_m\ s^2/(ku + k)] = [(V_m\ s^2)/\ k(\rho_o - \rho_d)]d\rho_\infty/ds \tag{36}$$

Conservation of pollutant,

$$V_m\ C_m\ s^2/(ku + k) = D^2\ V_o\ C_o/4 \tag{37}$$

where

$$s^* = s/D \tag{38}$$

$$V_m^* = V_m/V_o \tag{39}$$

$$E^* = (V_m^* s^*/k^{1/2})^3 \tag{40}$$

$$R^* = [V_m^* \Delta_m s^{*2}]/[k(u+1)] \tag{41}$$

Substitution of (40) into (41) gives

$$R^* = [E^{*1/3} \Delta_m s^*]/[k^{1/2}(u+1)] \tag{42}$$

$$\rho_\infty^* = \rho_\infty/(\rho_o - \rho_d) \tag{43}$$

The angle of the plume's axis, θ, from the horizontal can be evaluated by considering conservation of horizontal momentum,

$$d/ds \int_0^\infty V^2 \cos\theta\ r\ dr = 0 \tag{44}$$

Substitution of equation (29) and simplifying using equation (40), results in

$$\theta = \cos^{-1}\ [(E_e^*/E^*)^{2/3} \cos\theta_e] \tag{45}$$

where θ_e is the plume inclination at s_e^*. Abraham (1963) shows that for a horizontal discharge,

$$\tan\theta = [1+(1/4)(s^*/s_e^*) + (1/6)(s^*/s_e^*)^2]s^*/F \tag{46}$$

For other than a horizontal discharge, Rittall and Baumgartner (1972 errata to Baumgartner et al. 1971) derived an expression for the angular orientation of the plume's axis at the end for the zone of flow establishment using a linear interpolation process and equation (46),

$$\text{Alpha} = (\text{Beta}/90^o)(90^o-\theta_e) + \theta_e \tag{47}$$

where Beta is the angular orientation of the discharge port from the horizontal. When Beta = 90^o, Alpha = 90^o, and when Beta = 0^o, Alpha = θ_e.

Model Description

The initial conditions for the zone of established flow are determined by evaluating θ_e, E^*, and R^* at $s^*=s_e^*$. The length of the zone of flow establishment as a function of the initial Froude number is

$$s_e^* = 2.8\ F^{2/3} \qquad F< 2 \tag{48}$$

$$s_e^* = 0.113\ F^2 + 4 \qquad 2 \leq F\leq 3.2 \tag{49}$$

$$s_e^* = (5.6\ F^2)/(F^4 + 18)^{1/2} \qquad F> 3.2 \tag{50}$$

Assuming that the centerline concentration at s_e^* is equal to the initial concentration, $C_m = C_o$, and solving equation (37) for E^* as a function of s^*, gives

$$E^{*1/3} = [k^{1/2}(u+1)]/4s^* \tag{51}$$

which, when evaluated at $s^*=s_e^*$, gives the initial condition for E_e^*.

Assuming also that the centerline density at s_e^* is equal to the initial density and that there is no ambient stratification along the length of the zone of flow establishment, the centerline density disparity, Δ_m, defined by,

$$\Delta_m = (\rho_\infty-\rho_m)/(\rho_o-\rho_d) \tag{52}$$

is therefore equal to 1.

Substitution of equations (51) and (52) into equation (42) gives

$$R_e^* = 1/4$$

The angle θ_e is calculated from equation (46) with $s^*=s_e^*$ and together with the discharge port angle from the horizontal, the initial angle is then calculated with equation (47).

Equations (35) and (36) are solved at steps along the plume's axis by the Runge-Kutta approximation. E* is used to calculate the inclination θ and concentration C. The position of the plume's axis is incremented by

$$dx/ds = \cos\theta \tag{53}$$

$$dz/ds = \sin\theta \tag{54}$$

where x and z are the horizontal and vertical coordinates respectively.

The centerline concentration is inverted to describe the centerline dilution. To convert the centerline dilution to a flux-average dilution, the distribution of concentration must be weighted by distribution of velocity. With the distributions assumed for UPLUME, the flux-average dilution can be found by

$$S_a = 1.77\ (1/C_m) \text{ or } = 1.77\ S_m \tag{55}$$

where S_m is the centerline dilution. The model UPLUME produces flux-average dilutions and, for one output option, also gives centerline dilutions as did the model PLUME contained in Teeter and Baumgartner (1979). The dilution achieved for a plume trapped at a subsurface equilibrium level below 0.9 times the port depth is calculated from E* and S* at the elevation where R* is estimated to be zero, i.e., where the average density of the plume equals the ambient density. This is normally somewhat below the maximum height of rise, but is where similarity ends. Above this level, the plume tends to spread and become passive, possibly interfering with further dilution. If the plume reaches 0.9 times the port depth, then the plume is considered to reach the depth at which no further dilution is possible (due to blocking).

The centerline velocity, averaged over each step length, is divided into the step length to obtain time. The plume diameter is found by W=0.308s. The calculation of these parameters also ceases when the final dilution is calculated. The program terminates when the vertical velocity is zero, the angle of the centerline is 0^o, or the surface is reached, whichever occurs first.

UOUTPLM

Theoretical Development

The computer model OUTPLM (Winiarski and Frick 1976, 1978) considers a single plume element. By following the element as it gains mass due to ambient fluid entrainment, the characteristics of a continuous plume in a flowing ambient are described. The original cooling tower plume model has been adapted for marine discharges (Teeter and Baumgartner 1979). Density (or temperature and salinity) and velocity are assumed to be average properties of the element. The sums of plume element and entrained mass, horizontal momentum, and energy are conserved. An equation relating temperature, salinity, and density (U.S. Navy Hydrographic Office 1952) is used to calculate the density of the ambient and the plume element at each time step.

Entrainment brings ambient mass (plus momentum, temperature, and salinity) into the plume element. Entrainment is assumed to consist of either of two mechanisms. One mechanism, sometimes called forced entrainment, is due to the impingement of current on the plume. It is the mass flux through the boundary area of the plume element projected on a plane normal to the current. The element is usually a section of a bent cone. Therefore, the projected area formulation contains a cylindrical term, a growth term, and a curvature term as described in Frick (1984). The second mechanism is aspiration entrainment (i.e., the Taylor entrainment hypothesis discussed in Taylor et al. 1956) which captures 0.1 times the product of the external area of the plume element and its shear velocity. Total entrainment is taken to be the larger of these two mechanisms.

Model Description

In the computer program, the entrained mass is added to the element's mass to become the new mass. The new temperature and salinity of the element are the averages of the old values and the entrained ambient values weighted by their relative masses. The horizontal velocity is found in the same way, thus conserving horizontal momentum. The vertical velocity depends on buoyant force as well. The new density, and thus buoyancy, creates a vertical acceleration on the plume segment. Since the element is considered to be one of a train, each following the preceding element, drag is assumed to be negligible. The segment length is changed in proportion to the total velocity to conserve mass and pollutant. The radius is changed to correspond to the new mass and density. Dilution is calculated by comparing the initial volume to that of the element. The program terminates execution when the vertical velocity reaches zero, the surface is reached, or length scales or execution step limits are reached whichever occurs first.

UDKHDEN

Theoretical Development

UDKHDEN is a fully three-dimensional model which can be used for either single or multiple port diffusers and is based on the technical developments of Hirst (1971a,b), Davis (1975) and Kannberg and Davis (1976). It considers variable profiles through the zone of flow establishment and through the merging zone of multiple plumes. Detailed development of the plume is considered through the zone of flow establishment rather than by approximating it in a single step as do most other models. In addition, the changing geometric form of merging, multiple plumes is approximated instead of sharply transitioning from multiple, round plumes into a two dimensional equivalent slot plume.

UDKHDEN is easier to use than DKHPLM. Ambient conditions are entered in tabular form, thereby allowing for variation in density and/or current as a function of depth. The user can input either temperature and salinity, or density, for both the effluent and the receiving water characteristics. Entrainment is an explicit function dependent on the local Froude number, plume spacing, excess velocity, and ambient velocity. Similar profiles (power function form) are assumed for velocity, concentration, and temperature. These profiles are superimposed in their merging zones.

Zone of Flow Establishment

All quantities are assumed uniformly distributed in the plume at the point of discharge. In the zone of flow establishment, these uniform profiles change to similar profiles as the boundary layer diffuses inward to the centerline of the jet. The rate at which the profiles of velocity, concentration, and temperature develop may vary. The governing equations are

Conservation of mass:

$$d/ds \int_0^\infty Vrdr = E \qquad (56)$$

Conservation of energy:

$$d/ds \int_0^\infty V(T-T_\infty)rdr = -dT_\infty/ds \int_0^\infty Vrdr \qquad (57)$$

Conservation of pollutant:

$$d/ds \int_0^\infty V(C-C_\infty)rdr = -dC_\infty/ds \int_0^\infty Vrdr \qquad (58)$$

Conservation of momentum in the s equation:

$$d/ds \int_0^\infty V^2rdr = UEsin\theta_1cos\theta_2 + \int_0^\infty g(\rho_\infty-\rho)/\rho_d \; rdr \; sin\theta_2 \qquad (59)$$

where θ_1 is the horizontal angle between the plume centerline and the x axis, and θ_2 is the vertical angle between the plume centerline and the horizontal. Two additional integral equations have been developed from equation (59) to describe momentum in two additional plume coordinates. These "natural" coordinates of the plume are converted to conventional 3-dimensional Cartesian coordinates for model output. Implicit in the derivation of these equations are the assumptions that

- Flow is steady in the mean
- The fluid is incompressible and density variations are included only in the buoyant terms
- All other fluid properties are constant
- No frictional heating
- Pressure variations are purely hydrostatic
- Ambient turbulence effects are included in the entrainment function only
- Flow within the jets before merging is axisymmetric and is free, boundary layer type flow.

If temperature and salinities are input, densities are calculated internally using an equation relating temperature, salinity, and density (U.S. Navy Hydrographic Office 1952) in the subroutine SIGMAT. The six governing equations are solved simultaneously in the subroutine SIMQ and stepped forward in space by Hamming's modified predictor-corrector generator in subroutine HPCG. This procedure continues until velocity, temperature, and concentration profiles become fully developed. Subroutine OUTP1 contains the results which are stored as initial conditions for the zone of established flow.

Zone of Established Flow

The governing equations presented in the previous section are also solved in the zone of established flow but are slightly different in form. They are evaluated using a power function approximation to Gaussian profiles leaving the centerline concentrations, temperature, width, and plume coordinates as dependent variables. Entrainment is determined from an empirical function which is a function of plume size, excess velocity, local Froude number, and ambient velocity. Subroutine DERIV evaluates the derivatives of these dependent variables which are used in subroutine HPCG to step forward in space. Subroutine OUTP evaluates the values of the variables at each integration step and prints them out periodically.

Zone of Merging

When adjacent plumes begin to overlap, the plumes are no longer considered axisymmetric. The distributions of plume properties are superimposed as shown in Figure 3. The entrainment function is modified to account for the interaction of plumes and the reduction in the entrainment surface as the merging process proceeds. It is assumed that the plumes are equally spaced, in a line, and that end effects are negligible.

Sample Run and Model Listing

The program is for interactive operation from a terminal. The program contains many comments and explanations which serve as further model documentation and will aid the user in operating the model. Required inputs and resultant outputs are described in Section 5. The program is terminated when the surface is reached, when the preprogrammed length scale (SF=1000) is exceeded, the plume has reached its maximum height or error conditions were detected in subroutine HPCG (see comment section of that subroutine under IHLF) whichever occurs first.

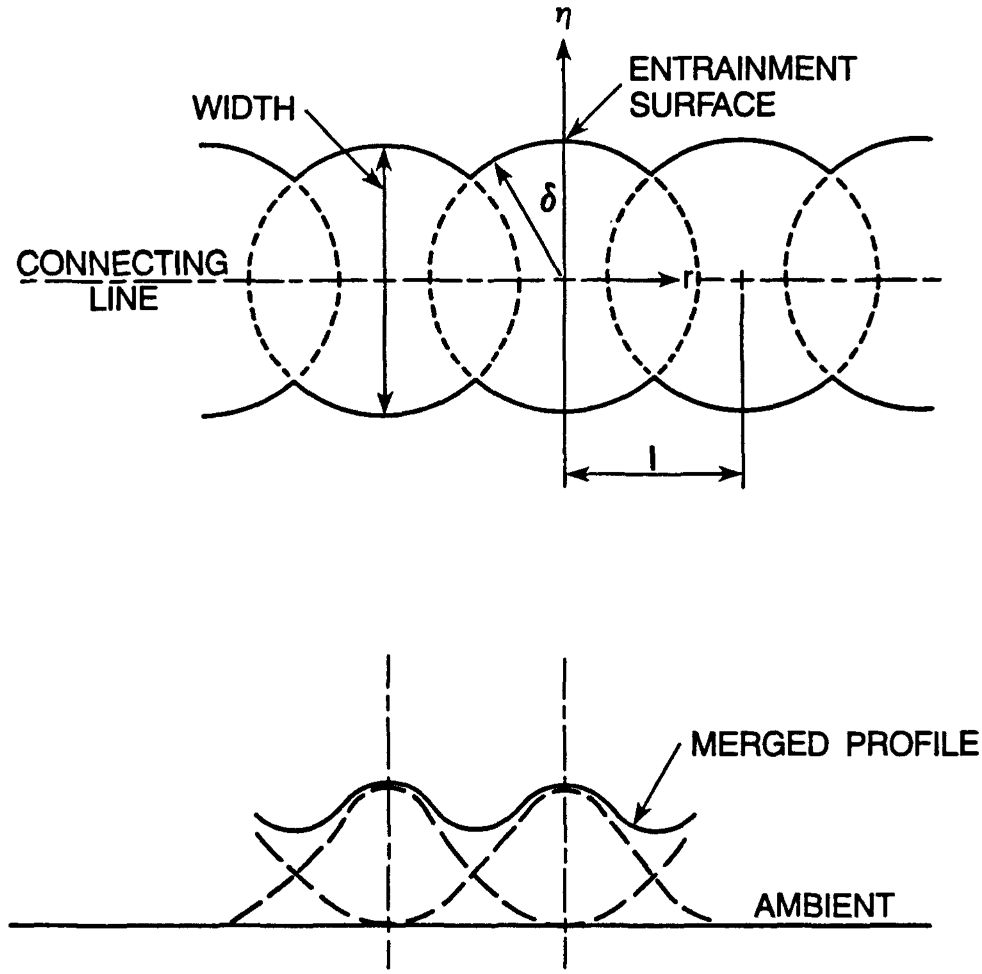


Figure 3. Cross section and profile along connecting line of merging plumes.

Theoretical Development

The model UMERGE analyzes a positively buoyant discharge by tracing a plume element through the course of its trajectory and dilution. Conditional controls, rather than conceptual limitations, prevent analysis of negatively buoyant discharges. UMERGE is a two-dimensional model which accounts for adjacent plume interference and which accepts arbitrary current speed variations with depth. Diffuser ports are assumed to be equally spaced and may be oriented at any common elevation angle. The current is assumed to be normal to the diffuser axis and the discharge velocity vector is assumed to be in the plane formed by the current direction and the vertical axis.

The basic plume equations are summarized as follows

$$dm/dt = \text{entrainment (Taylor hypothesis + forced continuity)} \quad (60)$$
$$d(mu)/dt = u_o(dm/dt) \text{ (conservation of horizontal momentum)} \quad (61)$$
$$d(mv)/dt = (\Delta\rho/\rho)mg \text{ (vertical momentum)} \quad (62)$$
$$d(mT)/dt = T_o(dm/dt) \text{ (conservation of temperature)} \quad (63)$$
$$d(mS)/dt = S_o(dm/dt) \text{ (conservation of salinity)} \quad (64)$$

$$\Delta h/(u^2+v^2)^{1/2} = \Delta h_i/(u_i{}^2+v_i{}^2)^{1/2} = \text{constant} \quad (65)$$

where

i = initial conditions
o = ambient conditions.

Equation (65) transforms the integral flux plume equations to their Lagrangian counterparts. Also required is an equation for density (subroutine SIGMAT) as a function of temperature and salinity (U.S. Navy Hydrographic Office 1952). The equations are integrated with respect to time.

Forced and aspiration entrainment (Taylor hypothesis, see Morton et al. 1956) are handled in much the same way as in UOUTPLM. However, rather than considering the larger of the two components as being the operative mechanism, they are considered additive, based on superimposed flow fields. In the absence of a current, entrainment is due solely to aspiration. At moderate current levels, entrainment is from both mechanisms but aspiration is somewhat reduced in the lee of the plume. In the presence of higher currents, entrainment is largely forced (Frick 1981, 1984).

The merging equations are based on purely geometric considerations. The mass of overlapping portions of adjacent plumes is redistributed by increasing the normal dimensions of the plumes, and entrainment is adjusted accordingly.

Assumptions inherent in the model formulation include

- Exchange between adjacent plumes does not change the average properties of a plume element (mirror imaging) but does affect the plume radius
- The model calculates average plume properties
- The ambient fluid is largely undisturbed by the presence of the plume
- No net pressure forces are exerted on the plume by the ambient and adjacent plume elements exert no net force on each other
- Energy and salinity are conserved
- Specific heat is considered to be constant over the range of temperatures observed in the system
- In addition to entrainment by aspiration, all fluid impinging on the projected area of the plume is entrained

- Current direction is assumed to be normal to the diffuser axis

- The plume boundary encloses all the plume mass.

Model Description

Entrainment is considered as the mass flowing through the projected plume area plus the aspirated quantity. While the concept is simple, the computation for the projected plume area is complex and the reader is referred to Frick (1984) for further development. The changes in mass (Δm) and time (Δt) are scaled internally by the model, allowing for a variable time step. This feature shortens execution time, important when using microcomputers or when using the program to optimize a design. The new plume element average horizontal velocity, temperature, and salinity are calculated using weighted averages of both the element and entrained masses. In calculating the vertical velocity, the effect of buoyancy is taken into account.

The subsequent position of the plume element is found by multiplying the new element velocity by the time increment and adding to the previous coordinates. The length of the plume element changes during each time increment due to the velocity gradient between the two faces of the element. Elongation, or contraction, can be estimated by comparing the element velocities between iterations. The effect of merging is estimated by distributing the overlapping mass to other portions of the plume, calculating the resulting changes in the element radius, and by adjusting entrainment terms.

Once all plume properties have been calculated for a given time step, the iteration process begins anew until the vertical velocity becomes negative (maximum rise), the surface is reached, or the maximum number of specified iterations is exceeded.

ULINE

The model ULINE is based on Roberts' (1977) uniform density flume experiments and is a generalization of Roberts' (1979b) discussion of dilution achieved in an arbitrarily stratified environment. The ambient current direction is assumed constant but no restriction is imposed on the current direction relative to the diffuser axis. The ambient current speed and ambient density are allowed to vary with depth.

The results of the flume experiments of Roberts (1977) are shown in Figure 2. As indicated, the minimum surface initial dilution S_m, for a fixed current direction relative to the diffuser axis (0, 45, or 90°), is given by

$$S_m = (UH/q)\ f_\theta(F) \tag{66}$$

where

f_θ = function dependent on θ

θ = current direction relative to the diffuser axis (a current flowing perpendicularly to the diffuser axis has $\theta = 90°$)

$F = U^3/g'q$

$g' = g(\rho_o - \rho_d)/\rho_d$.

The model ULINE linearly interpolates the results of Roberts for an arbitrary current angle. The average initial dilution S_a for a slot jet (Brooks 1973) is approximately

$$S_a = 1.41\ S_m \tag{67}$$

These relations are used to derive the function

$$\alpha = dS_a/dz = 1.41\ (U/q) f_\theta(F) \tag{68}$$

On the basis of mass conservation the plume density at a height h above the diffuser can be expressed as

$$\rho_j(h) = \bar{\rho}_a(h) + [\rho_e - \bar{\rho}_a(h)]/S_a \tag{69}$$

where

$\overline{\rho}_a(h)$ = ambient density over the height of rise
ρ_e = effluent density
S_a = average initial dilution

Equation (69) can be rewritten as

$$\rho_j(h) = [\rho_e + \overline{\rho}_a(h)(S_a - 1)]/S_a \tag{70}$$

where

$$\overline{\rho}_a(h) = \int_0^h \alpha(z)\rho_a(z)dz \Big/ \int_0^h \alpha(z)dz$$

and

$$S_a = \int_0^h \alpha(z)\ dz \tag{71}$$

$$\alpha(z) = 1.41\ U(z) f_\theta(F)/q \tag{72}$$

Trapping of the plume occurs if $\rho_a(h) = \rho_j(h)$ for some h. Otherwise the plume surfaces. The program ULINE numerically integrates the two integrals

$$\int_0^h \alpha(z)\rho_a(z)dz \tag{73}$$

and

$$\int_0^h \alpha(z)dz \tag{74}$$

by the trapazoidal rule, and uses their values to determine whether the plume is trapped. As indicated earlier, the initial dilution S_a is given by equation (71), where h is the plume height of rise.

The program terminates when the trapping level is reached or when the plume surfaces.

SECTION 5

MODEL EXECUTION

INTRODUCTION

The five models are written in FORTRAN IV-PLUS and are running on a PDP 11/70. The program listings, available in a separate volume, have statements specific to this PDP system and may need to be modified to conform to the user's system. For example, the third read statement in UDKHDEN is

```
READ(3,102,END=221,ERR=999)N11
```

which might have to be modified to something like

```
READ(3,102)N11
IF(EOF)GO TO 221     If no more cards[1] to read - STOP.
IF(ERR)GO TO 999     Input error, inform user and STOP.
```

Also, the terminology used in the following discussion is specific to the PDP 11/70 running the IAS operating system, and the user will have to make appropriate changes. For example, the PDP 11/70 system prompt is

```
PDS>
```

The models are set up to be run from a terminal and require a UNIVERSAL DATA FILE (UDF) which is described below. Assume, for example, the user wishes to run UPLUME (the program must be in the user's directory) and has created a UDF named MARC.IN. The following is a step by step procedure

---

[1]As used herein, the word card refers to a record or line of information.

for running this example from a terminal connected directly to the computer. To distinguish between system or program prompts and user responses, the latter are underlined. Each response is terminated with a carriage return indicated by <cr>. It should be noted that the file names (MARC.IN, MARC.OUT etc.) selected for the following examples can be replaced by names chosen by the user.

SWITCH THE TERMINAL ON

CTRL C	Type the letter C while holding the control key down to obtain computer recognition.

(System information will be displayed.)

PDS> LOGIN<cr>	
USER NAME? ____ <cr>	Your user name.
PASSWORD? ____ <cr>	Your password (system does not echo password).

(Messages to system users will be displayed.)

PDS> RUN UPLUME<cr>

*****PROGRAM UPLUME, AUGUST 1985*****

ENTER UDF NAME MARC.IN<cr>	Your input file name.
ENTER OUTPUT FILE NAME MARC.OUT<cr>	Your input file name.

15:09:00 SIZE 19K CPU: 2.68 STATUS: SUCCESS

The results of this example are in the user's directory with the file name MARC.OUT. To display or print the results, enter the following:

PDS> TYPE MARC.OUT<cr> — This response will display the results at the user's terminal.

or,

PDS> PRINT MARC.OUT<cr> — This response will send the results to the line printer.

PDS> LOGOUT<cr> — Ends terminal session.

(User identification, terminal number, time, date, connect and system utilization times will be displayed.)

BYE

UNIVERSAL DATA FILE DESCRIPTION

Each of the five models described requires particular input data. Although these data (port diameter, spacing, etc.) are similar, the previous versions of the models (Teeter and Baumgartner 1979), had unique input data formats. To simplify the use of the models, they have been modified so that any one will read the same input data file which is termed the UNIVERSAL DATA FILE (described below and in Appendix II). This file contains all the parameters required to execute each of the models. Further, parameters that were usually held constant and entered each time a model was run, (e.g., printout interval and aspiration coefficient) are now preprogrammed. However, the user may change these default values by setting the parameter ICUTOP=1 (Card 2) and including Card 5 with the new value(s). IF ICUTOP=0, Card 5 must be omitted. In an earlier version of one of the models, the data could be entered in English or metric units. All of these models now require metric units. To distinguish the new models from the old ones, they are now named UPLUME, UOUTPLM, UDKHDEN, UMERGE and ULINE.

A UDF consists of one or more sets of "card images" created and maintained with any editor. See Appendix II for the data required, the units of the variables and their limitations where appropriate.

Card 1 can be used to identify a particular data set in the UDF.

Card 2 is a control card providing the user with the following options:

INTER (Interactive Control variable)

If INTER=0

The programs will process this data set and go to the next set or exit if there are no more data sets in the UDF.

If INTER=1 (Interactive mode)

The programs will prompt the user for a run title which is useful for identifying successive interactive runs. The user responds by typing in a title for the run, terminated by a carriage return. The programs will process the data set and display the following results at the user's terminal:

- If the equilibrium level was reached or that the plume reached the surface.

- Reason for terminating calculations, e.g., VERTICAL VELOCITY went through zero.

- Depth of equilibrium level if appropriate.

- Average dilution.

CHANGE VARIABLES?

The user is asked if another run is to be made with the existing ambient data, YES or NO?

+ If NO, the programs go to the next data set or exit as the case may be.

+ If YES, the user is prompted for a run title. After entering this title,

    1. The present values of the parameters that may be changed are displayed. Each variable is numbered.

    2. The user responds with the number of the variable to be changed and is then prompted for the new value.

    3. After entering the new value, the user is asked if another variable is to be changed, YES or NO?

       If YES, 1, 2, and 3 are repeated.

       If NO, the programs compute the results using the new value(s) and the entire sequence is repeated, i.e., results are displayed and the user is asked if another run is to be made.

<u>IDFP (Input data file)</u>

If IDFP=0

The card images of the input data are not included as part of the output.

If IDFP=1

The card images of the input data as they exist in the UDF will be included in the output for that run. It will not reflect any changes made by the user in the interactive mode (INTER=1). These changes are shown in the heading of the results.

ICUTOP (Control Parameter Change)

If ICUTOP=Ø

Card 5 must be omitted from the data set. The programs will use the preprogrammed default values for those parameters defined on Card 5.

If ICUTOP=1

Card 5 must be included in the data set even if blank. If it's blank, the default values will be used. If it's not blank, the user's values will be used with that data set.

If ICUTOP=1 and Card 5 is omitted or if ICUTOP=Ø and Card 5 is included, an input conversion error will occur and the programs will exit even if there are more data sets in the UDF. Correct that data set and reenter the UDF.

Output Format Control Ø, 1, or 2

IPI=IPO, IOI=IOO, IDI=IDO, IMI=IMO, ILI=ILO

If zero, the output format is 8-1/2 inches wide by 11 inches long. It may be longer depending on how many images of Card 7 are in the data set.

If one, the output format is as originally programmed; varies depending on the model.

If two, the output is condensed by omitting the results of intermediate iterations (except UDKHDEN). When in the interactive mode (INTER=1), the ambient data is not repeated but pertinent parameters are.

Card 3 contains the flow rate and all but one of the required diffuser parameters.

Card 4 contains a uniform ambient current speed (used in UOUTPLM only), the horizontal angle of the current relative to the diffuser and the discharge port spacing which is discussed below.

Card 5 is omitted if ICUTOP=Ø, included if ICUTOP=1. This card permits the user to change the default values of the programs.

Card 6 contains the number (NPTS) of images of Card 7 (ambient data table) included in the data set and the density of the discharge as either g/cm^3 or salinity (ppt) and temperature (^oC).

Card 7 is the ambient data table, one card for each depth of ambient data. Density may be in g/cm^3 or salinity (ppt) and temperature (^oC) All however must be in the same units. The number of cards must be equal to NPTS or an input conversion error will occur and the programs will exit even if there are more data sets in the UDF.

The order of the ambient data table is immaterial as all the programs sort this table, arranging the depths in increasing order.

All of the programs have a subroutine (LIMITS) to check that certain input data are within prescribed limits, e.g., the port depth cannot be zero meters or deeper than the deepest depth of the ambient data table. If INTER=1 (interactive mode), the user is prompted for corrections which may be made from the terminal. See the comments at the beginning of SUBROUTINE LIMITS in each of the programs for the specific data that is checked for that program.

DISCHARGE PORT SPACING

Selecting values for port spacing, flow rate, number of ports, and port diameter may not be that straightforward. The variety of diffuser designs requires the user of these models to exercise care in selecting values to use as input data.

For the simple case where all the ports are on the same line, equally spaced, discharging at the same angle and all the same diameter, the input values may be taken directly from the design data sheet(s). However, this is usually not the case and the data need to be modified to represent the simple case, and multiple runs may be needed to simulate segments of the diffuser.

One of the requirements for a well designed diffuser is that the flow rate per port be uniform (or nearly so) and thus the data are readily reduceable to any number of ports. Do not however reduce the data to a single port as at least two ports are required for adjacent port merging to be detected (see footnotes a and b to Table 2). If the port diameter is varied from one end to the other, usually in groups, and ports are all in the same line, the port diameter (PDIA, card 3) is a variable which may be easily changed by running the model interactively (INTER=1, card 2). The value to use for NP (card 3) is the number of ports in the group; the flow rate (QT, card 3) is NP times the flow rate per port; and the spacing (SPACE, card 4) is the distance between adjacent ports on the same side of the diffuser.

Often, diffuser designs specify half the ports to be on one side and the other half diametrically opposite or with staggered spacing, and all the same diameter. For this condition, model one side of the diffuser and verify that merging with plumes from the other side does not occur. Then, the results represent the dilution achievable based on adjacent ports. In this case, QT would be equal to half the total flow, NP equal to half the total number of ports and SPACE is the distance between adjacent ports on the same side of the diffuser.

All possible diffuser designs cannot be covered here but this should give the user some insight into selecting input data so the models give realistic results.

EXAMPLE UNIVERSAL DATA FILE

This UDF contains three data sets for the three printout options and is formatted using short field terminators.

UDF file name; User's choice. (For this example it is MARC.IN.)

```
#1 EFFLUENT & AMBIENT DENSITY AS G/CM3, ZERO CURRENT, IxI=IxO=ZERO
0,1,0,0,0,0,0,0,
1.266,148,.0915,0.,55.2,
0.,90.,3.0,
7,.99744,0.,
00.00,1.02261,,,
20.00,1.02275,,,
45.00,1.02302,,,
50.00,1.02344,,,
55.00,1.02348,,,
60.00,1.02365,,,
60.96,1.02367,,,
#2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1
0,1,0,1,1,1,1,1,
1.266,148,.0915,0.,55.2,
0.02,90.,3.0,
7,.99744,0.,
00.00,34.72,26.75,0.02,
20.00,34.72,26.30,0.02,
45.00,34.66,25.30,0.02,
50.00,34.74,24.10,0.02,
55.00,34.71,23.90,0.02,
60.00,34.71,23.30,0.02,
60.96,34.71,23.23,0.02,
#3 EFFLUENT & AMBIENT DENSITY AS G/CM3, 0.04 M/SEC CURRENT, IxI=IxO=2
0,1,0,2,2,2,2,2,
1.266,148,.0915,0.,55.2,
0.04,90.,3.0,
7,.99744,0.,
00.00,1.02261,,0.04,
20.00,1.02275,,0.04,
45.00,1.02302,,0.04,
50.00,1.02344,,0.04,
55.00,1.02348,,0.04,
60.00,1.02365,,0.04,
60.96,1.02367,,0.04,
```

Shown below is the second data set in this UDF formatted according to the individual card format specified in the description of the UDF.

```
#2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1
 0 1 0 1 1 1 1 1
      1.266        148      .0915       0.0       55.2
       0.02       90.0        3.0
          7     .99744        0.0
      00.00      34.72      26.75      0.02
      20.00      34.72      26.30      0.02
      45.00      34.66      25.30      0.02
      50.00      34.74      24.10      0.02
      55.00      34.71      23.90      0.02
      60.00      34.71      23.30      0.02
      60.96      34.71      23.23      0.02
```

In this example, the total effluent flow is 1.266 m^3/sec with a density of 0.99744 g/cm^3. The diffuser has 148 0.0915-m diameter ports spaced 3.0 m apart. The discharge is horizontal at a depth of 55.2 m. The ambient current is zero for the first case, a uniform current of 2.0 cm/sec 90 degrees to the diffuser for the second case and 4.0 cm/sec also at 90 degrees for the third case. For Cases 1 and 3, the density option is used; Case 2 uses the salinity-temperature option.

For this example the programs will print a "card image" (IDFP=1) of the data on the first page of the output with the results on the second page. This is shown in the following exhibits for UPLUME only, as it would be the same for the others. The results of the first data set will be the 8-1/2 by 11 format (IxI=IxO=Ø). The second will be as "originally" programmed (IxI=IxO=1) and the third will be the condensed format (IxI=IxO=2). UDKHDEN and ULINE do not have output format options.

RESULTANT MODEL OUTPUT

Four of the five models were run with this UDF. Table 2 shows the input parameters required by each model. Tables 3 through 6 define the output parameters for UPLUME, UOUTPLM, UDKHDEN, and UMERGE. No intermediate results are output for ULINE, and thus no table of output variables is necessary. Exhibits 1 through 6, and 8 through 10 show the output for both the original and new formats for the three models UPLUME, UOUTPLM, and UMERGE. UDKHDEN has only one output format (Exhibit 7, Case 2).

Even though the printed ambient densities for Case 2 (salinity-temperature option) are identical to the input ambient densities for Cases 1 and 3, (density option) the results are slightly different (UPLUME, Exhibits 1 and 2). This is because the number of significant digits used in the calculations involving densities are not the same. Cases 1 and 3 use six significant digits, but the number of digits used in Case 2 depends on the specific computer system and whether the programs are compiled using single or double precision. Case 2 densities are calculated values. Therefore the resulting number of significant digits may vary. This applies to the others programs as well but is not evident in the respective Exhibits as Cases 2 and 3 have ambient currents of 2.0 and 4.0 cm/sec respectively.

Another UDF (MARC2.IN), shown below, was run with ULINE. The interactive control (INTER=1) was used to show first the 8 1/2 x 11 format and then the condensed output (Exhibit 11). A uniform current of 4.0 cm/sec is included and the ambient current angle to the diffuser is varied; 90 45, and zero degrees.

```
EFFLUENT & AMBIENT DENSITY AS G/CM3, IxI=IxO=2
1,0,0,2,2,2,2,2,
1.266,148,.0915,90,55.2,
0.04,90.,3.0,
7,.99744,0.,
00.00,1.02261,,0.04,
20.00,1.02275,,0.04,
45.00,1.02302,,0.04,
50.00,1.02344,,0.04,
55.00,1.02348,,0.04,
60.00,1.02365,,0.04,
60.96,1.02367,,0.04,
```

BATCH PROCESSING

While these programs are designed to be run in the interactive mode from a terminal, they may also be run in batch mode. This mode does not require the attention of the user or tie-up a terminal while the program is running. This is especially useful for long runs, say 12 different density profiles with 5 different flows per profile which would tie-up a terminal for a considerable length of time. All systems provide this alternative but require job control language (JCL) cards, a special file or something similar. The PDP 11/70 requires a special file (filetype.BIS) containing the necessary instructions. To run UPLUME using MARC.IN data in batch mode on a PDP 11/70, the .BIS file is shown below. Before submitting the job, check to be sure that INTER=zero in every data set in the input file or the job will terminate prematurely.

Name of file, MARC.BIS

```
$JOB MARC DON (MIN)
$RUN UPLUME
MARC.IN
MARC.OUT
$PRINT/DELETE MARC.OUT
$EOJ
```

The first line is the user identification; DON is to receive the output, and (MIN) is the time in minutes which overrides system default time-cut for BATCH jobs. The second line identifies the program to be run. The third and forth lines identify the input and output files respectively. The fifth line prints and then deletes the output file and the last line terminates the job. Note that the third and forth lines do not have the dollar sign ($). This means that information is in response to program prompts and in the interactive mode would be entered from the terminal during program execution.

To run the model, the user responds to PDS prompts as shown below.

PDS> SUBMIT MARC<cr> (.BIS is the default filetype for the SUBMIT command.)
PDS> LOGOUT<cr>

The system puts the job in a queue and runs it along with time sharing tasks. Alternately, it may be submitted as a night job in which case it would not be run until after 10:00 pm. For this, the response to the PDS prompts is shown below.

PDS> SUBMIT/NIGHT MARC<cr>
PDS> LOGOUT<cr>

TABLE 2. UNIVERSAL DATA FILE PARAMETERS REQUIRED BY THE COMPUTER MODELS

Parameter	UPLUME	UOUTPLM	UMERGE	UDKHDEN	ULINE
QT	X	X	X	X	X
NP	X[a]	X[a]	X[a]	X[a]	X[b]
PDIA	X	X	X	X	
VANG	X	X	X	X	
PDEP	X	X	X	X	X
UW		X			
HANG				X	X
SPACE[a]	X	X	X	X	X[b]
NPTS	X	X	X	X	X
S	X	X	X	X	X
T	X	X	X	X	X
DP( )	X	X	X	X	X
SA( )	X	X	X	X	X
TA( )	X	X	X	X	X
UA( )			X	X	X

[a] SPACE is used to determine if merging of adjacent plumes occur if NP>1. If NP=1, then SPACE=1000 (DEFAULT) and the merging flags are inactive.

[b] In ULINE, the length of the diffuser is defined as the product of (NP-1) and SPACE. NP=1 is not allowed.

Blanks (no X) indicate parameters ignored by those models.

QT	Total effluent flow (m^3/sec)
NP	Number of ports
PDIA	Port diameter (m), effective diameter if known (Fischer et al. 1979)
VANG	Vertical angle of discharge (90^o is vertical)
PDEP	Depth of discharge (m)
UW	Ambient current speed (m/sec)
HANG	Horizontal angle of current relative to the diffuser
SPACE	Spacing between ports on the same side of the diffuser
NPTS	Number of cards in the ambient data table
S	Effluent salinity (ppt) or density (gm/cm^3) if T=zero
T	Temperature of the effluent (^{o}C) or zero if S is density
DP	Depth (m)
SA	Salinity (ppt) at DP or density (gm/cm^3) if TA=zero
TA	Temperature (^{o}C) at DP or zero if SA=density
UA	Current speed (m/sec) at DP

TABLE 3. OUTPUT PARAMETERS FOR UPLUME

Description	Original	New
A time based on the centerline velocity	T	T
Distance of the plume element from the port orifice along the centerline	S	S
Horizontal distance of the center of the plume element from the port orifice	X	X
Depth of plume element from the surface	Z	Z
Diameter of plume element	D	DIA
Height of rise of plume element	ELEV	H
Angle (degrees) of the plume's velocity (or centerline) at time T from the horizontal	THETA	THETA
Plume dilution[a]	DILN[a]	FLUX-AVG DILUTION

[a] In Teeter and Baumgartner (1979), DILN is the centerline dilution. In program UPLUME for IPI=IPO=1, both centerline dilution and flux-averaged dilution (which is 1.77 times the centerline dilution) are printed. For the other two print options, only flux-average dilution is printed. The flux-averaged dilution is the appropriate dilution to use in water quality computations.

EXHIBIT 1 UPLUME OUTPUT FOR IPI=IPO=0

```
UNIVERSAL DATA FILE: MARC.IN

#1 EFFLUENT & AMBIENT DENSITY AS G/CM3, ZERO CURRENT, IxI=IxO=ZERO
0,1,0,0,0,0,0,0,
1.266,148,.0915,0.,55.2,
0.,90.,3.0,
7,.99744,0.,
00.00,1.02261,,,
20.00,1.02275,,,
45.00,1.02302,,,
50.00,1.02344,,,
55.00,1.02348,,,
60.00,1.02365,,,
60.96,1.02367,,,

UPLUME VERSION 1.0 AUGUST 1985 (BASED ON OS3 VERSION 2.3 9/12/77)
................. ................. ................. .................
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #1 EFFLUENT & AMBIENT DENSITY AS G/CM3, ZERO CURRENT, IxI=IxO=ZERO


PRINTOUT INTERVAL                     =    3.       (DEFAULT)

INITIAL DENSITY OF THE PLUME          =    0.99744 G/CM3
DISCHARGE VELOCITY                    =    1.301   M/S
FROUDE NUMBER                         =    8.5

 DEPTH    DENSITY
  0.00    1.02261
 20.00    1.02275
 45.00    1.02302
 50.00    1.02344
 55.00    1.02348
 60.00    1.02365
 60.96    1.02367

TOTAL EFFLUENT FLOW                   =    1.2660  CMS
NUMBER OF PORTS                       =   148
PORT DIAMETER                         =    0.0915  M
PORT SPACING                          =    3.00    M
VERTICAL PORT ANGLE FROM HORIZONTAL   =    0.0     DEGREES
PORT DEPTH                            =   55.20    M

                                                                  FLUX-AVE
     T         S         X         Z         DIA        H      THETA  DILUTION
   (SEC)      (M)       (M)       (M)        (M)       (M)     (DEG)
    5.89      3.38      2.51     53.32       1.04      1.88     68.6     18.95
   14.70      6.38      3.21     50.42       1.96      4.78     81.1     54.79
   25.16      9.36      3.58     47.46       2.88      7.74     84.0     98.05
PLUMES MERGED, PARAMETERS AT THAT TIME WERE:
   26.67      9.74      3.62     47.08       3.00      8.12     84.1    102.99
FOLLOWING CALCULATIONS DO NOT ACCOUNT FOR MERGING, A SINGLE PLUME IS ASSUMED.
             12.33      3.89     44.50                10.70     83.0
             15.32      4.68     41.71                13.49      0.0

COMPUTATIONS CEASE:  PLUME TRAJECTORY IS HORIZONTAL

TRAPPING LEVEL   =  46.58 M BELOW WATER SURFACE.
AVERAGE DILUTION = 108.7
TIME TO TRAP: 28.48 SEC.  PLUME DIA AT THE TRAPPING LEVEL:  3.16 M
```

EXHIBIT 2 UPLUME OUTPUT FOR IPI=IPO=1

```
UNIVERSAL DATA FILE: MARC.IN

#2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1
0,1,0,1,1,1,1,1,
1.266,148,.0915,0.,55.2,
0.02,90.,3.0,
7,.99744,0.,
00.00,34.72,26.75,0.02,
20.00,34.72,26.30,0.02,
45.00,34.66,25.30,0.02,
50.00,34.74,24.10,0.02,
55.00,34.71,23.90,0.02,
60.00,34.71,23.30,0.02,
60.96,34.71,23.23,0.02,

OS3 PLUME VERSION 2.3  9/12/77 (MODIFIED FOR UNIVERSAL DATA FILE, AUGUST 1985.)
*****************A BUOYANT PLUME IN A DENSITY STRATIFIED MEDIA*****************
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1


CASE NO.  2 WITHIN THE UDF, UNITS: MKS, INITIAL CONDITIONS....

  PORT ANGLE . . . . . . . . . . . . .   0.0
  FROUDE NUMBER. . . . . . . . . . . .   8.5
  LENGTH FOR FLOW ESTABLISHMENT. . . .   0.51
  INTEGRATION STEP LENGTH. . . . . . .   0.062
  PRINTOUT INTERVAL. . . . . . . . . .   3.00
  XO . . . . . . . . . . . . . . . . .   0.51
  ZO . . . . . . . . . . . . . . . . .  55.14
  DISCHARGE DENSITY. . . . . . . . . .   0.99744
  PORT DEPTH . . . . . . . . . . . . .  55.20
  FLOWRATE . . . . . . . . . . . . . .   1.2660
  NUMBER OF PORTS. . . . . . . . . . . 148
  DISCHARGE VELOCITY . . . . . . . . .   1.30
  PORT DIAMETER. . . . . . . . . . . .   0.0915
  PORT SPACING . . . . . . . . . . . .   3.000

DENSITY STRATIFICATION:  DEPTH      RHO

                          0.00    1.02261
                         20.00    1.02275
                         45.00    1.02302
                         50.00    1.02344
                         55.00    1.02348
                         60.00    1.02365
                         60.96    1.02367

     T         S         X         Z         D         ELEV      THETA    DILN(CL)   DILN(AVE)
   6.00      3.43      2.53     53.28      1.06       1.92      69.0      10.92      19.33
  14.94      6.45      3.22     50.35      1.99       4.85      81.2      31.58      55.89
  25.54      9.46      3.59     47.36      2.91       7.84      84.1      56.17      99.42
PLUMES MERGED, PARAMETERS AT THAT TIME WERE:
  26.66      9.74      3.62     47.08      3.00       8.12      84.1      58.23     103.07
FOLLOWING CALCULATIONS DO NOT ACCOUNT FOR MERGING, A SINGLE PLUME IS ASSUMED.
            12.45      3.91     44.39                10.81      82.8
            15.35      4.71     41.70                13.50       0.0
LAST LINE ABOVE IS FOR MAXIMUM HEIGHT OF RISE.
TRAPPING LEVEL IS  46.58 M WITH CL DILUTION OF   61.4 AND AVE. DILUTION OF  108.7
TIME TO TRAP: 28.46 SEC.  PLUME DIA AT THE TRAPPING LEVEL:  3.16 M
HEIGHT OF RISE= 15.6 PERCENT OF DEPTH
```

EXHIBIT 3 UPLUME OUTPUT FOR IPI=IPO=2

```
UNIVERSAL DATA FILE: MARC.IN

#3 EFFLUENT & AMBIENT DENSITY AS G/CM3, 0.04 M/SEC CURRENT, IxI=IxO=2
0,1,0,2,2,2,2,2,
1.266,148,.0915,0.,55.2,
0.04,90.,3.0,
7,.99744,0.,
00.00,1.02261,,0.04,
20.00,1.02275,,0.04,
45.00,1.02302,,0.04,
50.00,1.02344,,0.04,
55.00,1.02348,,0.04,
60.00,1.02365,,0.04,
60.96,1.02367,,0.04,

UPLUME VERSION 1.0 AUGUST 1985 (BASED ON OS3 VERSION 2.3 9/12/77)
.................  .................  .................  .................
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #3 EFFLUENT & AMBIENT DENSITY AS G/CM3, 0.04 M/SEC CURRENT, IxI=IxO=2


INITIAL DENSITY OF THE PLUME        =    0.99744 G/CM3
DISCHARGE VELOCITY                  =    1.301   M/S
FROUDE NUMBER                       =    8.5

 DEPTH    DENSITY
  0.00    1.02261
 20.00    1.02275
 45.00    1.02302
 50.00    1.02344
 55.00    1.02348
 60.00    1.02365
 60.96    1.02367

TOTAL EFFLUENT FLOW                 =    1.2660  CMS
NUMBER OF PORTS                     =  148
PORT DIAMETER                       =    0.0915  M
PORT SPACING                        =    3.00    M
VERTICAL PORT ANGLE FROM HORIZONTAL =    0.0     DEGREES
PORT DEPTH                          =   55.20    M

COMPUTATIONS CEASE:  PLUME TRAJECTORY IS HORIZONTAL

NOTE:  AVERAGE DILUTION WAS 103.0 WHEN PLUMES
MERGED AT  47.08 M BELOW THE WATER SURFACE.
TRAPPING LEVEL NOT YET REACHED.  AVE. DILUTION
SHOWN BELOW DOES NOT ACCOUNT FOR MERGING.

TRAPPING LEVEL   =  46.58 M BELOW WATER SURFACE.
AVERAGE DILUTION = 108.7
TIME TO TRAP: 28.48 SEC.  PLUME DIA AT THE TRAPPING LEVEL:  3.16 M
```

TABLE 4. OUTPUT PARAMETERS FOR UOUTPLM

Description	Original	New
Horizontal distance of plume from port orifice	X	X
Depth of plume from the surface	Z	Z
Plume radius	B	PLUME RADIUS
Thickness of plume element in the numerical integration scheme	THICK	
Mass of plume element	MASS	
Entrainment due to impingement of the ambient current on the plume	EINS	
Aspiration entrainment	ZWEI	
Plume dilution	DILUTION	DILUTION
Density of plume minus ambient density expressed in sigma units	DENDIFF	DENDIFF
Horizontal component of the plume's velocity	HOR VEL	HORIZ VEL
Vertical component of the plume's velocity	VER VEL	VERT VEL
Magnitude of the plume's velocity	TOT VEL	TOTAL VEL
Temperature of plume minus ambient temperature (No heading printed if density option used)	TEMPDIF	

EXHIBIT 4 UOUTPLM OUTPUT FOR IOI=IOO=0

```
UOUTPLM VERSION 1.0 AUGUST 1985 (BASED ON OS3 VERSION 2.3 5-16-79)
................. ................. ................. .................
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #1 EFFLUENT & AMBIENT DENSITY AS G/CM3, ZERO CURRENT, IxI=IxO=ZERO

INITIAL THICKNESS OF PLUME ELEMENT  = PORT RADIUS (DEFAULT)
IMPINGEMENT ENTRAINMENT COEFFICIENT =     1.00    (DEFAULT)
ASPIRATION ENTRAINMENT COEFFICIENT  =     0.10    (DEFAULT)
NUMBER OF STEPS ALLOWED             =  5000       (DEFAULT)
PRINTOUT INTERVAL                   =    50       (DEFAULT)

AMBIENT CURRENT SPEED               =     0.00    M/S
INITIAL DENSITY OF THE PLUME        =    -2.5600  SIGMAT UNITS
FROUDE NUMBER                       =     8.5

 DEPTH   SIGMAT
  (M)
  0.00    22.61
 20.00    22.75
 45.00    23.02
 50.00    23.44
 55.00    23.48
 60.00    23.65
 60.96    23.67

TOTAL EFFLUENT FLOW                 =     1.2660  CMS
NUMBER OF PORTS                     =   148
PORT DIAMETER                       =     0.0915  M
PORT SPACING                        =     3.00    M
VERTICAL PORT ANGLE FROM HORIZONTAL =     0.0     DEGREES
PORT DEPTH                          =    55.20    M
```

X (M)	Z (M)	PLUME RADIUS (M)	DILUTION	DENDIFF (SIGMA)	HORIZ VEL (M/S)	VERT VEL (M/S)	TOTAL VEL (M/S)
0.00	55.20	0.05	1.0	26.05	1.30	0.00	1.30
0.00	55.20	0.05	1.0	25.87	1.29	0.00	1.29
0.09	55.20	0.06	1.4	18.42	0.92	0.02	0.92
0.22	55.19	0.09	2.0	13.02	0.65	0.03	0.65
0.41	55.18	0.13	2.8	9.21	0.46	0.05	0.46
0.66	55.13	0.18	3.9	6.51	0.33	0.08	0.34
1.00	55.01	0.24	5.5	4.60	0.23	0.11	0.26
1.40	54.74	0.31	7.8	3.25	0.16	0.14	0.22
1.79	54.29	0.39	11.1	2.30	0.11	0.17	0.20
2.15	53.64	0.47	15.6	1.62	0.08	0.18	0.19
2.47	52.81	0.57	22.1	1.14	0.06	0.18	0.19
2.76	51.76	0.69	31.2	0.80	0.04	0.17	0.18
3.03	50.45	0.85	44.1	0.56	0.03	0.16	0.17
3.28	48.82	1.05	62.4	0.31	0.02	0.15	0.15
3.53	46.76	1.37	88.2	0.07	0.01	0.13	0.13
*****PLUMES MERGE AT 46.04 M BELOW THE SURFACE WITH AN AVE. DILUTION OF 97.6							
*****FOLLOWING CALCULATIONS DO NOT ACCOUNT FOR MERGING							
*****NORMAL TRAPPING LEVEL REACHED							
3.86	43.93	2.05	124.8	-0.08	0.01	0.08	0.08
4.46	41.21	4.69	154.7	-0.09	0.01	-0.01	0.01

```
NUMBER OF STEPS=  732

COMPUTATIONS CEASE:  VERTICAL PLUME VELOCITY WENT THRU ZERO
PLUMES MERGED BEFORE TRAPPING LEVEL REACHED

TRAPPING LEVEL=  45.97 M BELOW WATER SURFACE, DILUTION=  98.52
```

EXHIBIT 5 UOUTPLM OUTPUT FOR IOI=IOO=1

..........OUTFALL BUOYANT (JET) PLUME IN FLOWING, STRATIFIED AMBIENT..........
UOUTPLM VERSION 1.0 AUGUST 1985 (BASED ON OS3 VERSION 2.3 5-16-79)
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1

E= 1.00 A= 0.10 ITERB= 5000 IR= 50
PORT SPACING (M) = 3.00, PORT DIA (M) = 0.0915, PORT ANGLE (DEG) = 0.0

AMBIENT STRATIFICATION	DEPTH,M	SALIN	TEMP,C	SIGMAT
	0.00	34.72	26.75	22.61
	20.00	34.72	26.30	22.75
	45.00	34.66	25.30	23.02
	50.00	34.74	24.10	23.44
	55.00	34.71	23.90	23.48
	60.00	34.71	23.30	23.65
	60.96	34.71	23.23	23.67

....

K	FROUDE	Q	CURRENT
6.50E+01	8.50E+00	8.55E-03	2.00E-02

-----MODEL INPUT (LINE 1) AND MODEL OUTPUT-----

X	Z	B	THICK	MASS	EINS	ZWEI	DILUTION	DENDIFF	HOR VEL	VER VEL	TOT VEL
0.00E-01	5.52E+01	4.57E-02	4.57E-02	3.00E-01	1.63E-04	1.72E+00	1.00E+00	2.60E+01	1.30E+00	0.00E-01	1.30E+00
1.56E-03	5.52E+01	4.59E-02	4.54E-02	3.02E-01	1.63E-04	1.72E+00	1.01E+00	2.59E+01	1.29E+00	3.08E-04	1.29E+00
9.38E-02	5.52E+01	6.40E-02	3.26E-02	4.24E-01	6.61E-05	2.89E-03	1.40E+00	1.84E+01	9.26E-01	1.57E-02	9.26E-01
2.27E-01	5.52E+01	8.99E-02	2.33E-02	6.00E-01	1.43E-04	4.09E-03	1.97E+00	1.30E+01	6.60E-01	3.31E-02	6.61E-01
4.17E-01	5.52E+01	1.26E-01	1.67E-02	8.49E-01	3.24E-04	5.78E-03	2.78E+00	9.21E+00	4.73E-01	5.42E-02	4.76E-01
6.82E-01	5.51E+01	1.74E-01	1.23E-02	1.20E+00	7.62E-04	8.19E-03	3.92E+00	6.51E+00	3.40E-01	8.06E-02	3.50E-01
1.04E+00	5.50E+01	2.36E-01	9.52E-03	1.70E+00	1.73E-03	1.16E-02	5.54E+00	4.60E+00	2.46E-01	1.12E-01	2.71E-01
1.46E+00	5.47E+01	3.04E-01	8.08E-03	2.40E+00	3.48E-03	1.65E-02	7.82E+00	3.25E+00	1.80E-01	1.43E-01	2.30E-01
1.90E+00	5.43E+01	3.77E-01	7.44E-03	3.39E+00	6.15E-03	2.33E-02	1.11E+01	2.30E+00	1.33E-01	1.64E-01	2.12E-01
2.33E+00	5.37E+01	4.60E-01	7.06E-03	4.80E+00	9.96E-03	3.30E-02	1.56E+01	1.62E+00	1.00E-01	1.74E-01	2.01E-01
2.74E+00	5.28E+01	5.61E-01	6.71E-03	6.79E+00	1.55E-02	4.67E-02	2.21E+01	1.14E+00	7.66E-02	1.75E-01	1.91E-01
3.15E+00	5.18E+01	6.86E-01	6.35E-03	9.60E+00	2.37E-02	6.60E-02	3.12E+01	7.99E-01	6.00E-02	1.70E-01	1.80E-01
3.56E+00	5.05E+01	8.41E-01	5.96E-03	1.36E+01	3.61E-02	9.33E-02	4.41E+01	5.57E-01	4.83E-02	1.62E-01	1.69E-01
4.01E+00	4.89E+01	1.04E+00	5.49E-03	1.92E+01	5.64E-02	1.32E-01	6.24E+01	3.11E-01	4.00E-02	1.51E-01	1.56E-01
4.55E+00	4.68E+01	1.35E+00	4.64E-03	2.72E+01	9.76E-02	1.86E-01	8.82E+01	7.35E-02	3.42E-02	1.27E-01	1.32E-01
*****NORMAL TRAPPING LEVEL REACHED											
*****PLUMES MERGE, WHICH IS NOT ACCOUNTED FOR IN THE FOLLOWING CALCULATIONS											
5.42E+00	4.40E+01	1.99E+00	2.99E-03	3.84E+01	2.50E-01	2.58E-01	1.25E+02	-8.55E-02	3.00E-02	7.95E-02	8.50E-02
6.63E+00	4.18E+01	3.50E+00	1.36E-03	5.43E+01	3.75E-01	4.74E-02	1.76E+02	-7.92E-02	2.71E-02	2.76E-02	3.86E-02
7.33E+00	4.14E+01	5.16E+00	8.93E-04	7.68E+01	5.31E-01	1.37E-02	2.50E+02	-5.93E-02	2.50E-02	4.46E-03	2.54E-02
7.52E+00	4.14E+01	5.34E+00	8.72E-04	8.06E+01	5.57E-01	2.82E-02	2.60E+02	-5.66E-02	2.48E-02	-1.59E-03	2.48E-02

NUMBER OF STEPS= 807

COMPUTATIONS CEASE: VERTICAL PLUME VELOCITY WENT THRU ZERO
PLUMES MERGED AFTER TRAPPING LEVEL REACHED

TRAPPING LEVEL= 46.00 M BELOW WATER SURFACE, DILUTION= 99.06

EXHIBIT 6 UOUTPLM OUTPUT FOR IOI=IOO=2

```
UOUTPLM VERSION 1.0 AUGUST 1985 (BASED ON OS3 VERSION 2.3 5-16-79)
................. ................. ................. .................
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #3 EFFLUENT & AMBIENT DENSITY AS G/CM3, 0.04 M/SEC CURRENT, IxI=IxO=2


INITIAL THICKNESS OF PLUME ELEMENT  = PORT RADIUS (DEFAULT)
IMPINGEMENT ENTRAINMENT COEFFICIENT =      1.00    (DEFAULT)
ASPIRATION ENTRAINMENT COEFFICIENT  =      0.10    (DEFAULT)
NUMBER OF STEPS ALLOWED             =   5000       (DEFAULT)

AMBIENT CURRENT SPEED               =      0.04    M/S
INITIAL DENSITY OF THE PLUME        =     -2.5600  SIGMAT UNITS
FROUDE NUMBER                       =      8.5

 DEPTH   SIGMAT
  (M)
  0.00    22.61
 20.00    22.75
 45.00    23.02
 50.00    23.44
 55.00    23.48
 60.00    23.65
 60.96    23.67

TOTAL EFFLUENT FLOW                 =      1.2660  CMS
NUMBER OF PORTS                     =    148
PORT DIAMETER                       =      0.0915  M
PORT SPACING                        =      3.00    M
VERTICAL PORT ANGLE FROM HORIZONTAL =      0.0     DEGREES
PORT DEPTH                          =     55.20    M

NUMBER OF STEPS=  843

COMPUTATIONS CEASE:  VERTICAL PLUME VELOCITY WENT THRU ZERO
PLUMES MERGED AFTER TRAPPING LEVEL REACHED

TRAPPING LEVEL=  46.03 M BELOW WATER SURFACE, DILUTION= 100.69
```

TABLE 5. OUTPUT PARAMETERS FOR UDKHDEN

Parameter	Description
X	Horizontal distance perpendicular to the ambient current.
Y	Horizontal distance parallel to the ambient current.
Z	Vertical distance from the discharge port.
TH1	Local horizontal flow angle relative to the X coordinate. TH1 tends to approach 90 degrees in all cases. Initially, the horizontal angle of the ambient current with respect to the diffuser (90 degrees is perpendicular).
Note:	If the ambient current is zero, set TH1=90, then X will be parallel and Y will be perpendicular to the diffuser.
TH2	Initially, angle of the discharge port with respect to the horizontal (0 degrees is horizontal). Thereafter, its the angle of the plume's centerline with respect to the horizontal.
WIDTH	Initially the plume diameter. If merging does not occur, WIDTH is plume diameter. If merging occurs, WIDTH is the width of the plume.
DUCL	Excess velocity: (U(cl)-U(a))/(U(o)-U(ao)) U(cl) Instantaneous plume centerline velocity. U(a) Ambient current velocity at U(cl) depth. U(o) Initial discharge velocity. U(ao) Ambient current velocity at the depth of discharge.
DRHO	Excess density, defined the same ways as for DUCL except densities instead of velocities.
DCCL	Ratio of instantaneous centerline concentration of a tracer to the discharge concentration of that tracer, assuming an ambient concentration of 0.0.
TIME	Time in seconds.
DILUTION	Average dilution.

And not shown here but will replace DUCL and DCCL when the temperature and salinity option is used:

DTCL	Excess temperature, defined the same was as for DUCL except temperatures instead of velocities.
DSCL	Excess salinity, defined the same way as for DUCL except salinities instead of velocities.

EXHIBIT 7 UDKHDEN OUTPUT (NO OPTIONS)

PROGRAM UDKHDEN
SOLUTION TO MULTIPLE BUOYANT DISCHARGE PROBLEM WITH
AMBIENT CURRENTS AND VERTICAL GRADIENTS. AUG 1985

UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1
DISCHARGE= 1.2660 CU-M/S DENSITY=0.99744 G/CM3 ** DIAMETER= 0.0915-M
** NUMBER OF PORTS= 148 ** SPACING= 3.00-M ** DEPTH= 55.20-M

AMBIENT STRATIFICATION PROFILE

DEPTH (M)	DENSITY (G/CM3)	VELOCITY (M/S)
0.00	1.02261	0.020
20.00	1.02275	0.020
45.00	1.02302	0.020
50.00	1.02344	0.020
55.00	1.02348	0.020
60.00	1.02365	0.020
60.96	1.02367	0.020

FROUDE NO= 8.50, PORT SPACING/PORT DIA= 32.79, STARTING LENGTH= 0.570

ALL LENGTHS ARE IN METERS-TIME IN SEC. FIRST LINE ARE INITIAL CONDITIONS.

X	Y	Z	TH1	TH2	WIDTH	DUCL	DRHO	DCCL	TIME	DILUTION
0.00	0.00	0.00	90.00	0.00	0.09	1.000	1.000	1.000	0.00	1.00
0.00	0.57	0.03	90.00	6.68	0.25	1.000	0.993	0.993	0.44	2.00
0.00	1.27	0.22	90.00	25.85	0.74	0.349	0.308	0.308	1.52	6.71
0.00	1.86	0.66	90.00	46.08	1.23	0.249	0.157	0.157	3.43	13.24
0.00	2.30	1.24	90.00	57.79	1.74	0.214	0.091	0.092	5.82	22.48
0.00	2.65	1.88	90.00	63.86	2.28	0.193	0.059	0.059	8.53	34.54
0.00	2.96	2.54	90.00	67.07	2.85	0.178	0.041	0.041	11.52	49.36
PLUMES MERGING										
0.00	3.23	3.22	90.00	68.37	3.38	0.168	0.030	0.031	14.73	65.44
0.00	3.50	3.90	90.00	69.11	3.80	0.164	0.024	0.025	18.06	80.11
0.00	3.76	4.59	90.00	69.67	4.18	0.160	0.020	0.021	21.47	94.42
0.00	4.01	5.28	90.00	70.07	4.55	0.156	0.016	0.018	24.97	108.47
0.00	4.26	5.96	90.00	70.03	4.98	0.146	0.010	0.015	28.62	122.23
0.00	4.77	7.33	90.00	68.29	6.15	0.113	0.000	0.011	37.12	148.07
PLUMES HAVE REACHED EQUILIBRIUM HEIGHT - STRATIFIED ENVIRONMENT										
0.00	5.13	8.18	90.00	65.66	7.68	0.093	-0.004	0.009	43.80	162.82
0.00	5.45	8.83	90.00	61.85	9.10	0.079	-0.007	0.009	49.94	173.88
0.00	5.83	9.46	90.00	54.49	11.23	0.061	-0.009	0.009	57.21	184.01
0.00	6.33	9.99	90.00	36.05	14.63	0.037	-0.013	0.009	66.80	192.31
0.00	7.02	10.15	90.00	-14.07	16.85	0.024	-0.014	0.009	80.69	195.61

PLUMES HAVE REACHED MAXIMUM HEIGHT - STRATIFIED ENVIRONMENT

TRAPPING LEVEL= 47.79 METERS BELOW SURFACE, DILUTION= 149.49

TABLE 6. OUTPUT PARAMETERS FOR UMERGE

Description	Original	New
Iteration step number	J	
Horizontal distance of plume from port orifice	HOR COR (X)	X
Depth of plume from the surface	DEPTH (Z)	Z
Plume diameter	DIAMETER	PLUME DIAMETER
Plume dilution	VOL DIL	DILUTION
Horizontal component of the plume's velocity	HOR-VEL (V)	HORIZ VEL
Vertical component of the plume's velocity	VER-VEL (V)	VERT VEL
Magnitude of the plume's velocity	TOTAL VEL	TOTAL VEL
Density of plume minus ambient density expressed in sigma units	DEN-DIFF	DENDIFF
Ambient current (horizontal)	CURRENT	AMBIENT CURRENT
Time (seconds) of plume from the port orifice	TIME	

EXHIBIT 8 UMERGE OUTPUT FOR IMI=IMO=0

UMERGE VERSION 1.0 AUGUST 1985.

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UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #1 EFFLUENT & AMBIENT DENSITY AS G/CM3, ZERO CURRENT, IxI=IxO=ZERO

```
ASPIRATION ENTRAINMENT COEFFICIENT  =    0.10     (DEFAULT)
NUMBER OF STEPS ALLOWED             =  5000       (DEFAULT)
ITERATION PRINTOUT FREQUENCY        =   150       (DEFAULT)
PRINT ARRAY AA (0=NO, 1=YES)        =    0        (DEFAULT)
PRINT ARRAY AB (0=NO, 1=YES)        =    0        (DEFAULT)
PRINT ARRAY AC (0=NO, 1=YES)        =    0        (DEFAULT)

INITIAL DENSITY OF THE PLUME        =   -2.5600   SIGMAT UNITS
FROUDE NUMBER                       =    8.5
```

DEPTH (M)	SIGMAT	U (M/S)
0.00	22.61	0.000
20.00	22.75	0.000
45.00	23.02	0.000
50.00	23.44	0.000
55.00	23.48	0.000
60.00	23.65	0.000
60.96	23.67	0.000

```
TOTAL EFFLUENT FLOW                 =    1.2660   CMS
NUMBER OF PORTS                     =   148
PORT DIAMETER                       =    0.0915   M
PORT SPACING                        =    3.00     M
VERTICAL PORT ANGLE FROM HORIZONTAL =    0.0      DEGREES
PORT DEPTH                          =   55.20     M
```

FIRST LINE OF OUTPUT ARE INITIAL CONDITIONS

X (M)	Z (M)	PLUME DIAMETER (M)	DILU-TION	DENDIFF (SIGMAT)	HORIZ VEL (M/S)	VERT VEL (M/S)	TOTAL VEL (M/S)	AMBIENT CURRENT (M/S)
0.00	55.20	0.091	1.00	26.05	1.30	0.00	1.30	0.000
0.00	55.20	0.092	1.01	25.87	1.29	0.00	1.29	0.000
0.41	55.18	0.255	2.78	9.21	0.46	0.05	0.46	0.000
1.40	54.74	0.625	7.82	3.25	0.16	0.14	0.22	0.000
2.47	52.81	1.139	22.08	1.14	0.06	0.18	0.19	0.000
3.28	48.82	2.110	62.40	0.30	0.02	0.15	0.15	0.000
*****MERGING BEGINS								
*****NOMINAL TRAPPING LEVEL REACHED								
3.62	45.97	3.029	98.59	0.00	0.01	0.12	0.12	0.000

COMPUTATIONS CEASE: VERTICAL PLUME VELOCITY IS LESS THAN 0

PLUMES MERGED AND TRAPPED AT THE SAME TIME.
TRAPPING LEVEL = 45.97 M BELOW SURFACE; DILUTION = 98.52

EXHIBIT 9 UMERGE OUTPUT FOR IMI=IMO=1

UMERGE VERSION 1.0 AUGUST 1985.

CASE NUMBER 2 WITHIN THE UDF
UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1

NPTS= 7 A= 0.100 ITER= 5000 IFRQ= 150
NAA= 0 NAB= 0 NAC= 0

AMBIENT STRATIFICATION

DEPTH (M)	SALIN (PPT)	TEMP (C)	SIGMAT	U (M/S)
0.00	34.72	26.75	22.61	0.020
20.00	34.72	26.30	22.75	0.020
45.00	34.66	25.30	23.02	0.020
50.00	34.74	24.10	23.44	0.020
55.00	34.71	23.90	23.48	0.020
60.00	34.71	23.30	23.65	0.020
60.96	34.71	23.23	23.67	0.020

EFFLUX TO CURRENT RATIO(K) . . .= 65.0
DENSIMETRIC FROUDE NO. . . . . .= 8.5
VOLUME FLUX(M**3/S). . . . . . .= 0.009
DEPTH AVE STRATIFICATION PARM. .= 690393.2
DEPTH(M) . . . .= 55.20
DISCHARGE VELOCITY(M/S). . . . .= 1.301
CURRENT SPEED(M/S) . . . .= 0.020
PORT RADIUS(M) . . . .= 0.0457
NUMBER OF PORTS. . . . .= 148
VERTICAL DISCHARGE ANGLE . . . .= 0.0
PORT SPACING(M). . . . .= 3.00

MODEL OUTPUT AFTER -J- ITERATIONS (MKS UNITS) J=0 ARE INITIAL CONDITIONS

J	HOR COR(X)	DEPTH(Z)	DIAMETER	VOL DIL	HOR VEL(U)	VER VEL(V)	TOTAL VEL	DEN DIFF	TIME	CURRENT
0	0.000	55.200	0.091	1.000	1.301	0.000	1.301	26.042	0.000	0.020
1	0.002	55.200	0.092	1.007	1.292	0.000	1.292	25.863	0.001	0.020
150	0.405	55.181	0.252	2.781	0.473	0.053	0.476	9.207	0.588	0.020
300	1.412	54.778	0.612	7.821	0.180	0.138	0.227	3.250	4.410	0.020
450	2.692	52.898	1.125	22.076	0.077	0.173	0.190	1.140	15.739	0.020
600	3.947	49.038	2.094	62.397	0.040	0.149	0.155	0.321	39.478	0.020
*****MERGING BEGINS										
669	4.677	46.319	3.031	100.656	0.032	0.114	0.119	0.016	60.040	0.020
*****NOMINAL TRAPPING LEVEL REACHED										
673	4.733	46.125	3.122	103.485	0.032	0.111	0.116	0.000	61.770	0.020
750	6.550	42.181	13.474	176.477	0.027	0.024	0.036	-0.086	124.158	0.020

COMPUTATIONS CEASE: VERTICAL PLUME VELOCITY IS LESS THAN 0

PLUMES MERGED BEFORE TRAPPING LEVEL REACHED
TRAPPING LEVEL = 46.13 M BELOW SURFACE; DILUTION = 103.47

EXHIBIT 10 UMERGE OUTPUT FOR IMI=IMO=2

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UMERGE VERSION 1.0 AUGUST 1985.
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UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #3 EFFLUENT & AMBIENT DENSITY AS G/CM3, 0.04 M/SEC CURRENT, IxI=IxO=2


ASPIRATION ENTRAINMENT COEFFICIENT  =     0.10     (DEFAULT)
NUMBER OF STEPS ALLOWED             =  5000        (DEFAULT)
PRINT ARRAY AA (0=NO, 1=YES)        =     0        (DEFAULT)
PRINT ARRAY AB (0=NO, 1=YES)        =     0        (DEFAULT)
PRINT ARRAY AC (0=NO, 1=YES)        =     0        (DEFAULT)

INITIAL DENSITY OF THE PLUME        =    -2.5600   SIGMAT UNITS
FROUDE NUMBER                       =     8.5

 DEPTH   SIGMAT    U
  (M)             (M/S)

  0.00    22.61   0.040
 20.00    22.75   0.040
 45.00    23.02   0.040
 50.00    23.44   0.040
 55.00    23.48   0.040
 60.00    23.65   0.040
 60.96    23.67   0.040

TOTAL EFFLUENT FLOW                 =     1.2660   CMS
NUMBER OF PORTS                     =   148
PORT DIAMETER                       =     0.0915   M
PORT SPACING                        =     3.00     M
VERTICAL PORT ANGLE FROM HORIZONTAL =     0.0      DEGREES
PORT DEPTH                          =    55.20     M

COMPUTATIONS CEASE:  VERTICAL PLUME VELOCITY IS LESS THAN 0

PLUMES MERGED BEFORE TRAPPING LEVEL REACHED
TRAPPING LEVEL =  47.01 M BELOW SURFACE;  DILUTION = 130.35
```

EXHIBIT 11 ULINE OUTPUT FOR INTER=1 AND IXI=IXO=2

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ULINE VERSION 2.0 AUGUST 1985     A LINE SOURCE OF BUOYANCY FLUX ONLY
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UNIVERSAL DATA FILE: MARC2.IN
CASE I.D. EFFLUENT & AMBIENT DENSITY AS G/CM3, IxI=IxO=2

RUN TITLE:  CURRENT ANGLE PERPENDICULAR (HANG=90) TO THE DIFFUSER


ROBERTS FACTOR SA/SM                =     1.41    (DEFAULT)
INTEGRATION STEP SIZE               =     0.10    (DEFAULT)

INITIAL DENSITY OF THE PLUME        =     0.99744 G/CM3
ROBERTS FROUDE NUMBER               =     0.09

 DEPTH   DENSITY     U
  (M)    (G/CM3)   (M/S)
  0.00   1.02261   0.040
 20.00   1.02275   0.040
 45.00   1.02302   0.040
 50.00   1.02344   0.040
 55.00   1.02348   0.040
 60.00   1.02365   0.040
 60.96   1.02367   0.040

TOTAL EFFLUENT FLOW                 =     1.2660  CMS
NUMBER OF PORTS                     =   148
PORT SPACING                        =     3.000   M
HORIZONTAL ANGLE                    =    90.0     DEGREES
PORT DEPTH                          =    55.20    M

TRAPPING LEVEL =  46.60 M BELOW WATER SURFACE, DILUTION = 107.12

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

RUN TITLE:  CURENT ANGLE 45 DEGREES (HANG=45) TO THE DIFFUSER


ROBERTS FROUDE NUMBER               =     0.09

TOTAL EFFLUENT FLOW                 =     1.2660  CMS
NUMBER OF PORTS                     =   148
PORT SPACING                        =     3.000   M
HORIZONTAL ANGLE                    =    45.0     DEGREES
PORT DEPTH                          =    55.20    M

TRAPPING LEVEL =  46.48 M BELOW WATER SURFACE, DILUTION = 104.36

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

RUN TITLE:  CURRENT ANGLE PARALLEL (HANG=0) TO THE DIFFUSER


ROBERTS FROUDE NUMBER               =     0.09

TOTAL EFFLUENT FLOW                 =     1.2660  CMS
NUMBER OF PORTS                     =   148
PORT SPACING                        =     3.000   M
HORIZONTAL ANGLE                    =     0.0     DEGREES
PORT DEPTH                          =    55.20    M

TRAPPING LEVEL =  46.48 M BELOW WATER SURFACE, DILUTION = 104.36
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APPENDIX I

Development of S_a and h Relationship

A general relationship between plume average initial dilution and height of rise in a linearly stratified ocean can be developed as follows:

Let

$$S_a = \beta z^n \tag{75}$$

where

S_a = flux average initial dilution
β = coefficient
z = vertical coordinate, positive upward with origin at the discharge depth
n = constant greater than 0.

Also, describe a linear density profile as

$$\rho_a(z) = \rho_0 + az \tag{76}$$

where

ρo = ambient density at the discharge depth
ρa = constant ambient density gradient from the discharge depth to the water surface

Define

$$\alpha(z) = dS_a/dz = \beta n z^{n-1} \tag{77}$$

$$\int_0^z \alpha(z)dz = \beta z^n = S_a \tag{78}$$

Then

$$\int_0^z \alpha(z)\rho_a(z)dz = \int_0^z \beta n z^{n-1}(\rho_o + az) = \rho_o \beta z^n + [a\beta n z^{n+1}/(n+1)] \tag{79}$$

Therefore

$$\bar{\rho}_a(z) = [\rho_o \beta z^n + a\beta n z^{n+1}/(n+1)]/\beta z^n = \rho_o + [anz/(n+1)] \tag{80}$$

Assume the plume is trapped at z=h below the water surface.

At z = h

$$\rho_j(h) = \rho_a(h) \tag{81}$$

where

$\rho_j(h)$ = average density of the plume
$\rho_a(h)$ = ambient density at the equilibrium height

But the plume average density can be expressed as

$$\rho_j(h) = \bar{\rho}_a(h) + [\rho_d - \bar{\rho}_a(h)]/S_a \tag{82}$$

Therefore, from Equations (75) and (80),

$$\rho_j(h) = \rho_o + [anh/(n+1)] + \{(\rho_d - \rho_o) - [anh/(n+1)]\}/\beta h^n \tag{83}$$

Equating this to equation (76) at z=h results in

$$\rho_d - \rho_o - anh/(n+1) = (\beta h^n)(ah)/(n+1) = \beta a h^{n+1}/(n+1) \qquad (84)$$

In a "typical" ocean

$$\rho_d = 1 \text{ g/cm}^3$$

$$\rho_o = 1.025 \text{ g/cm}^3$$

$$\rho_{surface} = 1.024 \text{ g/cm}^3$$

Therefore

$$|\rho_d - \rho_o| = +0.025 \text{ g/cm}^3$$

$$|anh/(n+1)| < |ah| = 0.001 \text{ g/cm}^3$$

$$|anh/(n+1)| << |\rho_d - \rho_o|$$

Neglecting this term in (84) leads to

$$(n+1)(\rho_d - \rho_o) = \beta a h^{n+1} \qquad (85)$$

or

$$h = [(n+1)(\rho_o - \rho_d)/(-\beta a)]^{1/(n+1)} \qquad (86)$$

Rewriting

$$h = \{[(n+1)/\beta][g(\rho_o - \rho_d)/\rho_o][\rho_o/(-g d\rho/dz)]\}^{1/(n+1)} \qquad (87)$$

$$h = \{[(n+1)/\beta][g_d'/G]\}^{1/(n+1)} \qquad (88)$$

where

$G = -(g/\rho_o)\ d\rho/dz$

$$g_d' = g(\rho_o - \rho_d)/\rho_o$$

It should be noted that the neglect of the second term in Equation (84) is not necessary for the formulas of Roberts.

Substituting n=1 into Equation (84) gives

$$(\rho_d - \rho_o) - (ah/2) = \beta a h^2/2 \tag{89}$$

or

$$h^2 + (h/\beta) + 2(\rho_o - \rho_d)/\ a = 0 \tag{90}$$

or

$$h^2 + (h/\beta) - (2g_d'/\beta G) = 0 \tag{91}$$

which has a solution

$$h = (1/2\beta)[-1+(1+2g_d'\beta/G)^{1/2}] \tag{92}$$

APPENDIX II

UNIVERSAL DATA FILE (UDF) "CARD" DECK

THE DATA ENTERED ON CARDS 2 THROUGH 7 MAY BE EITHER IN THE FORMAT REQUIRED BY EACH CARD OR EACH VALUE ON THE CARD MAY BE SEPARATED BY A COMMA (SHORT FIELD TERMINATION). AN EXPLICIT DECIMAL POINT OVERRIDES THE FIELD DESCRIPTOR.

```
CARD 1  FORMAT(10A8)
        IDENTIFICATION OF A DATA SET WITHIN THE UDF.

CARD 2  FORMAT(8I2)
        INTER  =1 INTERACTIVE CONTROL OF CARDS 3 AND 4 PARAMETERS.
               =0 "SINGLE" RUN USING PARAMETERS IN DATA SET ONLY.
        IDFP   =1 PRINT "CARD IMAGE" OF DATA SET.
               =0 DO NOT PRINT CARD IMAGE OF DATA SET.
        ICUTOP =1 USE OPTIONAL CARD 5 TO CHANGE CONTROL PARAMETERS FROM
                  THE DEFAULT VALUES.
               =0 DO NOT READ A CARD 5 (THUS CARD 5 MUST BE OMITTED).

        IPI       INPUT PRINTOUT CONTROL FOR  UPLUME
        IOI                  "                UOUTPLM
        IDI                  "                UDKHDEN (SEE NOTE 1)
        IMI                  "                UMERGE
        ILI                  "                ULINE

        IPO=IPI   OUTPUT PRINTOUT CONTROL FOR UPLUME
        IOO=IOI              "                UOUTPLM
        IDO=IDI              "                UDKHDEN (SEE NOTE 1)
        IMO=IMI              "                UMERGE
        ILO=ILI              "                ULINE

        FOR EACH OF THE PARAMETERS IPI TO ILI
               =0 USE NEW (8.5 X 11) FORMAT.
               =1 USE ORIGINAL FORMAT.
               =2 USE CONDENSED FORMAT (USEFUL IN INTERACTIVE MODE).

           NOTE!  1)  IDI AND IDO ALLOWED FOR BUT PRESENTLY NOT USED
                      IN UDKHDEN, ENTER THE SAME VALUE AS THE OTHERS.

CARD 3  FORMAT(F10.0,I10,3F10.0)
        QT        TOTAL EFFLUENT FLOW (CUBIC METERS PER SEC).
        NP        NUMBER OF PORTS (SEE NOTE 2).
        PDIA      PORT DIAMETER (M), EFFECTIVE DIAMETER IF KNOWN.
        VANG      VERTICAL ANGLE (DEG) OF PORT RELATIVE TO THE
                  HORIZONTAL (90 DEGREES FOR A VERTICAL PORT).
                  ULINE ASSUMES VANG=90 DEG.
        PDEP      PORT DEPTH (M) MUST BE GREATER THAN 0.0 AND
                  LESS THAN OR EQUAL TO THE DEEPEST DEPTH OF THE
                  AMBIENT DENSITY PROFILE.

           NOTE!  2)  ULINE REQUIRES TWO OR MORE PORTS, FOR THE
                      OTHERS, IF NP=1 SPACE=1000.0 (DEFAULT) MAKING
                      THE MERGING FLAGS INACTIVE.

CARD 4  FORMAT(3F10.0)

        UW        HORIZONTAL CURRENT SPEED (M/S) (USED IN UOUTPLM ONLY).
        HANG      ANGLE (DEG) OF CURRENT DIRECTION WITH RESPECT TO DIFFUSER
                  AXIS (90 DEGREES CORRESPONDS TO A CURRENT DIRECTION
                  PERPENDICULAR TO THE DIFFUSER AXIS AND IF VANG=0, BOTH
                  THE CURRENT AND THE DISCHARGE ARE IN THE SAME DIRECTION)
                  (SEE NOTE 3).
        SPACE     DISTANCE (M) BETWEEN ADJACENT PORTS (SEE NOTE 2).

           NOTE!  3)  HANG NOT USED IN UPLUME.  UOUTPLM AND UMERGE
                      ASSUME 90 DEG.  UDKHDEN RANGE 45 - 135 DEG FOR
                      MORE THAN ONE PORT AND 0 - 180 DEG FOR A SINGLE
                      PORT (NOTE, SINGLE PORT ONLY:  FOR VALUES GREATER
```

THAN 90 DEG BUT LESS THAN OR EQUAL TO 180 DEG, THE
PROGRAM SETS HANG EQUAL TO THE SUPPLEMENTARY ANGLE).
ULINE RANGE 0 - 180 DEG.

CARD 5 OPTIONAL (INCLUDE THIS CARD ONLY IF ICUTOP =1)
FORMAT(F5.0,2I5,3I2,6F5.0,2I5)

USED IN UMERGE

A	ASPIRATION COEFFICIENT	0.1	BY DEFAULT
ITER	MAXIMUM NUMBER OF ITERATIONS	5000	BY DEFAULT
IFRQ	ITERATION PRINTOUT FREQUENCY	150	BY DEFAULT
NAA	PRINT ARRAY AA IF =1, DO NOT IF =0	0	BY DEFAULT
NAB	PRINT ARRAY AB IF =1, DO NOT IF =0	0	BY DEFAULT
NAC	PRINT ARRAY AC IF =1, DO NOT IF =0	0	BY DEFAULT

(SEE LISTING OF PROGRAM UMERGE FOR CONTENTS OF ARRAYS
AA, AB, AC WHICH ARE MAINLY DEBUGGING AIDS.)

USED IN UPLUME

PS	PRINTOUT "INTERVAL"	3.	BY DEFAULT

USED IN ULINE

RK	RATIO OF SA/SM IN ROBERTS' EXPERIMENTS	1.41	BY DEFAULT
DH	INTEGRATION STEP SIZE (M)	0.1	BY DEFAULT

USED IN UOUTPLM

H	INITIAL THICKNESS OF PLUME ELEMENT	.5*PDIA	BY DEFAULT
E	IMPINGEMENT ENTRAINMENT COEFFICIENT	1.0	BY DEFAULT
A	ASPIRATION ENTRAINMENT COEFFICIENT	0.1	BY DEFAULT
ITERB	NUMBER OF INTEGRATION STEPS ALLOWED	5000	BY DEFAULT
IR	PRINTOUT INTERVAL	50	BY DEFAULT

NOTE! WHEN CARD 5 IS USED, ALL OF THE PARAMETERS NEED NOT BE
GIVEN A NEW VALUE, ONLY THE ONES TO BE CHANGED. ENTER ZERO
FOR THE OTHERS AND THERE DEFAULT VALUES WILL BE USED.

ITER, IFRQ, ITERB AND IR NOT TO EXCEED FOUR DIGITS.

NO OPTIONS AVAILABLE FOR UDKHDEN.

CARD 6 FORMAT(I10,2F10.0)

NPTS — NUMBER OF DEPTHS WHERE AMBIENT TEMPERATURE, SALINITY, AND HORIZONTAL CURRENT SPEED ARE KNOWN (NPTS MUST BE AT LEAST EQUAL TO 2 AND NOT MORE THAN 30).

S — EFFLUENT SALINITY (PPT) IF T NOT EQUAL TO ZERO
EFFLUENT DENSITY (G/CM3) IF T=0

T — EFFLUENT TEMPERATURE (DEGREES CELSIUS).
IF T=0 PROGRAMS ASSUME S IS EFFLUENT DENSITY IN G/CM3, SEE NOTE 4.

CARD 7 FORMAT(4F10.0)

DP( ) — DEPTH IN METERS, MUST HAVE DATA FOR DP( )=0.0

SA( ) — AMBIENT SALINITY (PPT) IF TA( ) NOT EQUAL TO ZERO
AMBIENT DENSITY (G/CM3) IF TA( )=0

TA( ) — AMBIENT TEMPERATURE (DEGREES CELSIUS).
IF TA( )=0 PROGRAMS ASSUME SA( ) IS AMBIENT DENSITY IN G/CM3, SEE NOTE 4.

UA( ) — HORIZONTAL AMBIENT CURRENT SPEED (M/S) (USED IN UMERGE, UDKHDEN, AND ULINE).

NOTE! 4) THERE MUST BE NPTS IMAGES OF CARD 7. ALSO, EITHER ALL TA(I) MUST BE ZERO OR ALL NOT ZERO, OR ERRORS IN THE INTERPRETATION OF SA( ) AND TA( ) WILL OCCUR. IF, FOR SOME I, SA(I) IS DESIRED TO REPRESENT AMBIENT SALINITY AND TA(I) SHOULD BE EXACTLY 0, SET TA(I) EQUAL TO A SMALL NUMBER INSTEAD (0.000001 FOR INSTANCE). THIS APPLIES TO S AND T AS WELL.